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The Impact Response of Composite Materials Involved in Helicopter Vulnerability Assessment: Literature Review - Part 2

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ABSTRACT

The present review aims at a provision of scientific support to the introduction of the Tiger ARH (Armed Reconnaissance Helicopter) into service. The review examines more than five hundred recent publications on the impact response of composite and cellular materials which are constituents of modern air platforms, specifically, helicopters. Using the ARH in an operational environment makes ballistic damage assessment an important issue. This review focuses on the factors of material response associated with structure vulnerability, such as damage resistance and damage tolerance.

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Executive Summary

The present review examines studies of the impact response of composite and cellular materials. The review aims at the provision of scientific support for the introduction of the Tiger ARH (Armed Reconnaissance Helicopter) into service. Using the ARH in an operational environment makes ballistic damage assessment an important issue. In the majority of modern military air platforms, including helicopters, the skins, which protect vulnerable equipment and crew, are made of composite and cellular materials (the latter are also composites in a sense). Therefore, studies of the impact response of composite materials are particularly relevant to the helicopter vulnerability assessment.

An air platform's vulnerability is affected by both the structure design and properties of the materials forming the structure. The structure is vulnerable to loads before, during, and after an impact. The after-impact vulnerability also involves vulnerability of behind-skin equipment and crew. Therefore, evaluation of the reduction of a projectile's energy during penetration is one more aspect of the vulnerability assessment. A comprehensive assessment of the impact-related vulnerability also involves consideration of issues relating to an assessment of the ability of a damaged structure to be repaired and the structure vulnerability after the repair. Both these issues are identified in this review. Their detailed examination is, however, beyond the review scope.

This review consists of two Parts. Part 1 includes Sections 1-4. Section 1 formulates the purposes that governed this literature review and provides an outline of the paper. Section 2 focuses on structure certification and classification of threats; Section 3 – on material characterisation; and Section 4 – on general experimental techniques and theories used for studies of impact. Part 2 includes Sections 5-8. Section 5 reviews literature on damage response to low-velocity impact; Section 6 – on damage response to ballistic impact; and Section 7 – on after-impact evaluation characterised by damage tolerance and repair. Section 8, 'Conclusion' summarises trends and technology gaps in the area of impact response of composites.

Aircraft structure design imposes a number of restrictions on the properties of materials to be used. The restricting parameters could be seen as a subset of the design parameters. Formulation and establishment of the design parameters build up a process of certification. This process along with classification of threats is described in Section 2.

Characterisation of materials under loads before impact includes a determination of mechanical properties for static and dynamic conditions. This is a well-developed area of the mechanical engineering science. Typically the characterisation determines material's limiting stresses and strengths, including fracture onset. The methods that are applied to

conventional (metallic) materials can also be applied to the materials in modern helicopter structures. Section 3 outlines and examines the peculiarities of advanced material characterisation associated with anisotropy of materials and with strongly non-linear behaviour of foams. Non-destructive evaluation also deals with material characterisation from the viewpoint of the material quality and integrity. Relevant literature is reviewed in the last subsection of Section 3.

Material response to loads during impact is the most complex area of study, both theoretically and experimentally. The impact characterisation is not straightforward because it involves not only a determination of mechanical properties (such as the limit stresses and strengths at high strain rates) but also an analysis of the factors related to a large variety of the failure mechanisms sensitive to the impactor's characteristics such as shape and mass (which means sensitivity to the spatial and temporal distribution of the load). Also, the dynamic nature of the impact load should be taken into account, even for low-velocity impact. This rate sensitivity, having been noticed first in studies of conventional material response to impact, adds to the complexity of the advanced materials used in helicopter structures. Section 4 provides an overview of recent developments in this area.

Damage resistance and damage tolerance determine the skin capacity to reduce the impact threat. These factors relate to both the after-penetration energy of the impactor and the characterisation of the target response after impact. Damage resistance is an ability of the target material to resist the onset of damage and, thus, to protect the behind-target space against penetration of foreign objects. The material's protective properties against projectiles are characterised by the so-called 'ballistic limit'. The ballistic limit velocity is the most widely used characteristic of ballistic protection. It is linked with the energy that is absorbed by a target during a ballistic event. Damage tolerance is typically associated with the residual strength of the target material after impact. Material responds differently to low- and high-velocity impact threats. Section 5 provides an overview of studies of the damage tolerance at low-velocity impact (LVI). Issues of the ballistic damage resistance and tolerance are examined in Section 6.

The most dangerous mode of quasi-static loads to air structures susceptible to impact damage is believed to be compression. Therefore, a widely accepted characteristic of the damage tolerance is obtained with the Compression-After-Impact (CAI) test. This characteristic is called 'Compressive Strength After Impact' (CSAI). Publications focusing on the after-impact evaluation and on the after-impact repair of damaged structures are reviewed in Section 7.

Section 8, 'Conclusion', summarises the major issues and most relevant findings in the reviewed literature on composite and cellular material impact response. It also outlines current trends in theoretical and experimental studies of material characterisation for structures vulnerable to ballistic threats.

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5. Low Velocity Impact (LVI) damage and fracture

5.1 Damage mechanisms of composites under low-velocity impact

In order to simulate low-velocity impact, a variety of drop-weight machines are employed. A relatively low level of impact energy can also be achieved with a gas gun facility that can launch projectiles with impact velocities within a moderate range. A projectile interacts with a target longer under low-velocity impact (LVI), when compared with high-velocity impact. Therefore, LVI test interpretation involves a range of additional factors, occurring during the longer contact. LVI test results are usually described in terms of the load response from a target (the response is recorded by a load cell attached to the indentor) versus indentor displacement or the time of the deformation process. In general, this response has a peak force which drops abruptly after the penetration has occurred and the resistance of the damaged target to the indentor's penetration has reduced. A review of the relevant literature will be conducted below. It is obvious that LVI conditions provide enough time for stresses to propagate over a quite wide area and the damage is usually more extensive at lower impact velocity. The mechanisms of target damage during impact and the influence of these mechanisms on the Compression Strength After Impact (CSAI) is of primary interest to the majority of relevant studies and this topic will be addressed in Section 7.

Generally, the damage of a typical composite under low velocity impact develops in a way that is simulated in paper [Dechaene, 2002] for the LVI response of a composite fabric. Initially, the damage starts with matrix cracking at the distal side of a laminate, where tensile stresses are prevailing. The matrix-cracking type of damage gradually develops radially over a wider area and in the through-the-thickness direction, starting from the point at the distal side of the target, which is opposite to the projectile-target contact point. It should be noted that the damage does not usually reach the point of contact of the projectile with the target, where the compression stress state is established. Brittle matrices, which can fracture under compression, may behave differently. Delamination develops concurrently with matrix damage and the extent of this damage in laminated structural material depends on the interfacial strength between laminas. Finally, fibre breakage occurs, when the tensile stress achieves extreme magnitude in the fibres. The shear mechanism of damage under LVI conditions may play noticeable role for relatively thick targets. For thin targets this mechanism can be neglected as was shown with the FEM calculations in paper [Cho, 2002].

The paper [Dost, 1991] introduces a definition of a Characteristic Damage State (CDS), which is a function of material characteristics and conditions of loading. A disadvantage of this definition is the absence of a clear physical background and the uncertainty of load and material specifications (this CDS parameter may depend on different conditions of loading, stacking sequence, different modes of damage, etc., which makes the definition

vague). Therefore, the practical significance of this definition is not very high. Symmetric and asymmetric damage states, when inspecting delamination of target laminate under LVI in the through-thickness direction, are differentiated in the paper [Dost, 1991] for specified stacking sequences, where the CDS parameter is associated with the delamination resistance. Thus, in this work, the CDS is almost exclusively the delamination state, accompanied sometimes with the state of the fibre and matrix damage presented as failure of a ply.

The post-mortem examination of samples after impact is frequently used for assessment of damage resistance. For example, in paper [Khondker, 2005], the visible damage area after impact (e.g., the whitening area of the target's rear side, which is associated with the delamination) was linked with the damage resistance. A monotonic dependence of the resistance, which is defined in such manner, versus the impact energy was established in this paper. However, how this so-defined resistance is actually related to the capacity of the target to resist the impact is not clear from this study.

Which constituents of a composite contribute most to the damage resistance is the subject of theoretical and experimental studies reported in paper [Mieck, 2004]. This study claims that in the majority of cases, the fibres absorb the impact energy during Charpy tests. Thus, links between the composite strength, the fibre content and fibre tensile strength have been established.

Experiments reported in paper [Sun, 1987] are both low-velocity impact tests (pendulum ball impact) and high velocity (10-100 m/s) gas gun tests. Strain gauges were mounted on graphite/epoxy laminated samples subject to impact. After impact the samples were tested under tension in order to study the influence of impact damage on the residual strength. Three modes of damage were observed in the tests: matrix cracking, delamination, and fibre breakage. For low velocity impact, matrix cracking and delamination were the prevailing damage modes. A simple finite element approach, in order to simulate the impact response, was developed, using the Hertzian contact law approximation as a load law. The modelling results and correlation of the results with experimental data were used for the assessment of the effects of span, thickness and structure on the distribution of total and plastic energies. The plastic energy absorbed by the target plate, which is associated with the impactor's indentation, is claimed to be a parameter that is related to the residual strength degradation. The Hertzian law allows using the experimental indentation data in order to calculate the contact force. The rationale of the linear Hertzian law has been tested in paper [Choi, 2004], which enabled the authors to use a general purpose FEM-software. Numerical DYNA-analysis in paper [Her, 2004] has established the proportionality of the contact force to the projectile velocity, when using the Hertzian contact law for simulation of the low-velocity impact, where it was found that the duration of contact depends on the target stiffness.

Investigations of damage mechanisms are of traditional interest in after-impact inspection and testing of composites. Acoustic emission from flexure loading of composite samples subject to a low velocity impact (0-3J) has been traced in paper [Kwon, 1997] and this

emission was related to the impact damage. In the same study, C-scanning provided an evaluation of the delamination zones, where larger damage was observed at the distal side of impacted CFRP specimens. It was shown in paper [Kwon, 1997] that the emission level relates to the stress level and to the evaluated delamination for two CFRP laminates. A low-energy low-velocity impact against a composite target was considered in paper [Luo, 1999]. The material tested was a $[0_4/90_4]_S$ carbon/epoxy 2-mm thickness composite and the circular targets were 10 cm in diameter. After 0.59J impact these samples were inspected under a microscope, with X-ray photography, and with C-scanning. The fibres kept their integrity, but some signs of matrix failure and interlaminar delamination were noted. X-ray inspection was the most accurate for assessment of damage to the bottom layer of target. This damage was missed by the C-scan inspection. No damage was observed in the top layer of the target, where the compression state was established at the indentor-target contact point.

Pre-notched samples have been tested in paper [Salvi, 2003] under static and LVI conditions (the three-point bending Iosipescu tests) and inspection of the samples demonstrated a smaller damage zone under LVI conditions, when compared with static tests. More extensively developed secondary cracking was observed in the samples after tests under static conditions. This type of damage results in an increase of the absorbed energy in the static case. Higher localisation of the crack path was observed in the samples after dynamic tests. Load-deflection curves were obtained with a load cell embedded into the impactor and the displacement was calculated by double integration of the force divided by the impactor mass (from the second Newton's law). It was noted that the maximum load achieved was lower for dynamic tests, when compared with static tests. This comparison gives a quantitative evaluation of the energy decrease in the dynamic case, after the load-displacement curve is integrated to calculate the energy. It should be noted that the material tested in the paper [Salvi, 2003] is rather complex. The material's structure is actually a meso-structure where the stitched fibre tows (a homogeneous unidirectional structure) are moulded into a bulk material with matrix pockets between the tows. However, whether the material structure affects the damage response has not been discussed in this study.

A woven graphite/epoxy composite has been tested in paper [Shah Khan, 1998] with a drop weight machine where three-point bending test conditions were realised for pre-notched samples. The samples were instrumented with strain gauges that allowed stress to be evaluated (strain is actually measured, which can be associated with the stress via Hooke's law). A high-speed optical device was used for recording the indentor displacement. The displacement information was used for calculation of velocity (by differentiation). In turn, kinetic energies were calculated from the indentor velocities, and the difference of the kinetic energies before and after impact provided an estimate of the absorbed energy. The test and assessment results gave a linear dependence between absorbed energy and sample thickness. It should be noted that this method of calculation of the force-energy characteristics from the indentor displacement does not appear to be a reliable procedure because of the inevitable differentiation of the experimental displacement curves, which results in a significant magnification of experimental errors.

The in-plane character of damage for thin and thick composite samples has been observed in paper [Cantwell, 1990] regardless of the composite structure. Carbon/Epoxy laminate samples were tested under low- and high-velocity impact by balls below the critical impact energy (the impact energy, corresponding to the ballistic limit velocity, in other words, the perforation energy). The samples were manufactured in a beam shape (the beam width is 25 mm). At impact energy levels higher than the critical penetration energy, the facture zone (the cross sectional view) was of a truncated conical shape with the base at the distal surface of a sample. For low-velocity impact tests, the critical energy was linearly dependent on the target thickness (the thickness was varied from 0.5 up to 2mm). This dependence is bi-linear up to a beam thickness of 4 mm and it is strongly non-linear for the thicker samples (up to 8 mm in thickness). The conically shaped shear zones are observed in the micrographs. The dependence of the critical energy on sample span in the three-point bending appears to be linear, increasing with the span size (the span size was varied from 5 to 15 cm). This character of the dependence is explained by an increase of the elastic energy-absorbing capability with the span. Thus, this study shows the impossibility of assessing the low-velocity response of a structure by scaling (for example, to assess a large structure from small scale testing). Optical microscope analysis revealed large delamination zones far away from the point of impact. The delamination area was shown to have a quadratic dependence on the target thickness and this dependence is likely to be a linear function of the delamination diameter. Three major energy-absorbing mechanisms are suggested from the low velocity impact tests: elastic deformation, delamination and shear-out. Damage in the thick samples (8 mm in thickness) does not keep the regular conical shape (the cross sectional view). The dynamic tests (ball projectiles launched by a gas gun) discriminate two damage zones: a zone that is in the vicinity of the impact point and a zone that is close to the distal surface of the target. In fact, they could be treated as the hourglass shape zones reported in paper [Gellert, 2000]. A slight change of the perforation energy with beam span size was noticed only at a span size up to 8 cm. In general, the perforation energy does not depend significantly on the sample size due to the short response time of the target due to the high velocity of impact. This observation was supported by C-scanning, which demonstrated an approximately equal delamination size for all of the span sizes. The perforation energy dependence on target thickness is approximately the same for both the low-velocity and high-velocity impact cases. The damage mechanism for high-velocity impact appears to be different to the LVI case (for the LVI case, successive delamination was observed, which is associated with shear-out damage). In the high-velocity impact case, the damage mechanism is likely related to the two stages of shock loading with the pull out of material at the frontal surface (the material layers in the vicinity of the impact point) and fibre tearing at the rear (distal) surface of the target sample.

An analysis of a low-fibre E-glass composite subject to drop-weight machine testing is reported in paper [Sutherland, 2004]. The analysis showed significant shear damage with larger sample thickness (from 3 to 20 mm) due to the target 'stiffening' with the increase of the target thickness. The bending damage mechanism dominated for thin samples. With an increase of the impact energy, other failure modes were noted, including fibre

breakage. The maximum force achieved at the contact point during the tests (which was normalised by the plate thickness and squared) correlates linearly (piecewise linearly for the case of very thick plates) with the impact energy. This study and another study conducted by the same team for composites with various matrix resins (see paper [Sutherland, 2005a]) claim that delamination is the controlling parameter of the impact response of the composites for the whole range of impact energies up to the moment of fibre breakage.

An analysis of the dimensional effects for the impact of Glass/epoxy cross-ply composites has been conducted in paper [Aslan, 2002]. An instrumented drop weight machine has been used for testing samples and recording the force-time response of the composite material and the test results have been compared with FE calculations. A fair correlation of the experimental with numerical results was observed from the comparison, allowing delamination to be assessed from the calculations. It should be noted, however, that the validity of the extension of prediction of the force-time response to the evaluation of delamination area is not clear. Beam samples with a rectangular face were used in the tests. The sample thicknesses were 1.4 and 2.8 mm, the length span was 150 mm, and the width varied between 50, 100, and 150 mm. Even with such small variability in thickness, the study demonstrated a dependence of stiffness, peak load and contact time duration with the width to thickness ratio α (larger stiffness, larger peak load, and smaller duration were observed at smaller α). A stronger dependence of the predicted delamination area on thickness was reported in the study than a dependence of the delamination area on width (a smaller delamination was predicted for smaller α).

The time factor is very important during LVI. Relevant numerical analysis of an LVI event with the ABAQUS code has been conducted in paper [Breen, 2005] where a simple orthotropic elasticity model was used. A kinetic energy of 40 J was given to all impactors in these calculations. Keeping the impact energy constant, the velocity of impactors was varied from 2 up to 14 m/s. Even with the use of this simple material model, which ignores the composite material's heterogeneity and irreversible effects during the material deformation, the study demonstrated material behaviour features associated with the variation of the impact velocity. Examples of features simulated were the extent of the deformation localisation and the level of stresses which were developed in the target (which are higher if the impactor velocity is higher). Only two tests were conducted to validate the modelling (an impact test and a quasi-static test). Quite different cracking was observed for the two target laminates tested and a slightly higher localisation was observed for the dynamic test. A 20% reduction in the residual strength was shown for the dynamic test (the CAI test was performed in the 0° fibre direction of the surface ply). There is not enough data to conduct a statistical correlation for these two experiments, so it is difficult to decide if this result on target damage is more generally valid.

An extent of damage can be evaluated with X-ray inspection, provided that the overall damage is assessed, including the surface area of internal delamination, debonding, and structural imperfections introduced during loading. Quasi-static testing of a glass/polymeric composite at various loading rates (20 times variation) is reported in paper

[Zachariev, 2004]. The test instrumentation recorded the fracture force F_B increase with load rate increase, and X-ray inspection of the samples showed that the damage area (defined as an integral area mentioned above) increases with the current applied force F increase. However, the dependence of the damage on the loading rate disappears if the data are presented against the normalised force F/F_B. Therefore, this loading parameter is suggested in the paper [Zachariev, 2004] as a characteristic of the process.

A falling weight dart device was used in paper [Belingardi, 2002] for the testing of a laminated glass/epoxy composite with several stacking sequences. The weight velocity was controlled with an electro-optical device and was varied from 0.7 to 2.4 m/s. The force achieved at the end of the dart was measured by a load cell. Due to the inertia of the testing system the data have an oscillatory character and, therefore, they were filtered at 6 kHz. The target thickness was 2 mm. Several force thresholds were classified. The first damage force value, which has been associated also with the energy release rate G_{II}, was reached likely at the initialisation of damage and the maximum force when the laminate fails. A critical 'saturation' energy is defined as an integral of the force over time for the 'ballistic limit' case when the dart stops without rebound or penetration. Any increase in the dart's kinetic energy over this critical energy results in penetration. This critical energy can, obviously, be related to the absorption energy. The paper claims that there is no strain rate sensitivity of the force thresholds and the 'saturation' energy. However, it should be noted that the strain rate variation is relatively small (just less than 4 times) and therefore, judgement about the rate sensitivity of the data is limited. An attempt at evaluation of the absorbed energy from the SHPB data (stress-strain curves at different strain rates) has been conducted in paper [Shim, 2001]. However, this evaluation did not take into account that i) the stress response at the initial stage of loading cannot be associated with the equilibrium behaviour of material (that is, the energy calculated is not related to the material behaviour, it is related to the wave processes in the material); and ii) the stress drop, which is associated in this evaluation with material failure, may be caused by the load release due to a short incident pulse, so the absorbed energy is underestimated in this case.

Paper [Jang, 1989] considers a series of drop weight LVI tests up to 30 J-impact energy in order to assess the failure mechanisms of polymer-based fibre/epoxy (Aramid, Polyethylene, and Nylon fibres) and graphite/epoxy composites. The study claims that the polymer-based fibre composites exhibit higher loading rate sensitivity. The tests show that the ductility index (the ratio of the penetration energy to the energy that is calculated up to the moment when the maximum load has achieved) decreases with an increase of the total absorbed energy and impact energy (in contrast to the index behaviour for interleaved composites).

A study in paper [Baucom, 2003] has concentrated on the mechanisms of damage for E-glass 2D-plane-weave and 3D-orthogonal-weave composite systems with quasi-static indentation. This study demonstrated a wider spread of damage for 3D-systems (up to the edge of the samples), when compared with 2D-systems. This difference of the damage character in these composites was explained by the fact that the damage mechanism of the

3D-systems includes the straining of z-reinforcement tows, whereas the damage for the 2D-systems is highly localised. Matrix cracking, debonding, delamination, and fibre fracture have been observed in all of the systems. An interaction between the tows and the surface weft in the 3D-systems resulted in a larger spread of the damage area, when compared with the 2D-system and this damage delocalisation has lead to larger energy absorption.

5.2 Damage mechanisms of cellular materials under low-velocity impact

The applications of exotic materials such as honeycombs are quickly expanding in the aircraft industry. Specific modes of deformation and failure during response to impact are observed in such materials. The main feature of cellular material response is a high absorption capacity. When studying the LVI response of foams, the statically dominated material behaviour features involve load history effects (such as those manifested under repeated loads or during loading-unloading cycle). These effects might be activated by the creeping mode of deformation (see [Rizov, 2005]), which is typically negligible for composites.

Traditional testing approaches work reasonably well under static conditions for these materials. For example, foam-filled beams with aluminium face sheets have been tested in a three-point bending set-up in paper [Reyes, 2004] and the material failure was described well with either the critical load or critical failure strain criteria. The mechanism of collapse of cellular material typically involves a loss of stability and buckling of cell walls. Experimental observations made in paper [Papka, 1994], which were also confirmed in the paper by modelling results, have shown that for a honeycomb material with cells composed of 'weak' walls (i.e., thin walls or the walls made from material with a low yield limit) the collapse was occurring progressively in static test conditions. In this study [Papka, 1994] a weak-wall aluminium honeycomb material was collapsing row-by-row. On the other hand, for a honeycomb material with the cells composed of 'strong' walls the deformation at the compaction stage (the plateau stress response) was relatively homogeneous. Collapse of such a material occurred simultaneously for the cells over the whole volume of the material. This observation has also been confirmed by results of compression tests in static and dynamic conditions conducted in the paper [Baker, 1998] for aluminium and stainless steel honeycomb materials.

A study of the mechanism of damage of Polyurethane foam sandwich samples using LVI tests based on a pendulum testing machine has been reported in paper [Sharma, 2004a]. The testing machine used in this study has an inertia pendulum and a load-cell-instrumented-slider-tup that is subject to impact by the pendulum. Momentum is transmitted from the pendulum to the tup and further down to a target. The target assembly, which is joined with the slider, was equipped with a transducer in order to measure the displacement of the slider. This displacement was used to calculate indentation of the tup into a target. Thus, the load-displacement curves were taken during the impact. It should be noted that the intermediate slider part contributes to the inertia of

the indentor and this added inertia was probably not taken into account in the analysis. The analysis conducted in this paper resulted in the damage mechanisms of the sandwich structure occurring during failure in the following order: i) face sheet failure due to flexural and shear stress at the point of impact; ii) core failure due to delamination between the core and the face sheet and the shear of the core material; and iii) back face sheet failure due to bending caused by the delamination between the core and the back face sheet.

A study of the LVI response of an aluminium honeycomb sandwich material with aluminium face sheets has been reported in paper [Yu, 2003]. The hammer of a drop weight machine in this study was equipped with an embedded accelerometer (a loading cell) and the measurement records from this accelerometer were used for calculation of displacement. Because of the oscillatory character of the acceleration measurements, these records have been integrated in order to obtain velocity and the velocity data were filtered and differentiated in order to calculate force. This procedure does not appear to be reliable due to the numerical differentiation that amplifies the measurement errors, so interpretation of the load-displacement curves obtained with this routine should be taken with caution. General analysis of both the LVI and static tests results in the following damage mechanisms of the material tested: i) the compressive fracture mode takes place for the foam core in the vicinity of the impact point (with or without wrinkle of the upper face sheet) and the tensile fracture mode occurs at the distal side of the target; and ii) a higher localisation of damage occurs during the LVI tests, when compared with static tests, resulting in a lower absorption of energy for the dynamic tests. A study in the paper [Onck, 2004] has revealed possible fracture mechanisms of metallic foam materials during tensile testing, which are a brittle fracture mechanism due to the defects at casting and a ductile fracture mechanism due to necking, when straining a sample.

In paper [Sburlati, 2002], the applicability of the Hertzian contact law during indentation and LVI tests has been studied for sandwich foam materials. The indentation law exhibited a bi-linear character (obviously due to the initial resistance of the face sheets followed up by the core resistance). It was found that the Hertzian law is useful for high-density foam materials. For low-density foam materials, a high discrepancy between the predicted description and the experimental results was observed, when the prediction was based on the use of the dependencies of the indentation and force versus time.

The influence of the skinning of sandwich materials on LVI response has been studied for a hollow integrated E-glass honeycomb material (see paper [Hosur, 2004d]) and for a foam-filled integrated E-glass honeycomb material (see paper [Hosur, 2005a]). These foam-filled sandwich materials were skinned with carbon/epoxy or S2-glass/epoxy laminate face sheets. An instrumented drop weight machine was used with impact energies of 15, 30, and 45J. The load-deflection curves were obtained and used for evaluation of the damage resistance of the materials. Samples with the carbon/epoxy face sheets had a twice the damage resistance (peak load) of unskinned samples. Samples with the glass/epoxy face sheets increased the resistance three times (when compared with the

resistance of unskinned samples), thus demonstrating the maximum absorbed energy of the sandwich material in this instance.

In paper [Vaidya, 2003], a very cheap paper-core honeycomb material showed buckling and loss of stability of cells under impact at very low velocities. To improve the energy absorbing characteristics of this material the investigation [Vaidya, 2003] suggests the partial filling of the honeycomb core of this material with syntactic foam (this modified material has lower resistance characteristics than a fully filled material but, nevertheless, the partially filled material is more weight effective). LVI testing with an instrument impact machine demonstrated an increase of the peak load by 56% (increasing, thus, the impact resistance) for the partially foam-filled honeycomb sandwich materials with carbon/epoxy face sheets, when compared the peak load for the unmodified (unfilled) sandwich material. Thus, the study has shown that partial filling can be considered as cost and weight effective.

Paper [Mines, 1998] describes LVI tests of sandwich materials with composite face sheets, which were conducted with a drop-weight testing machine. The energy of the impacting weight was high (hundreds of J) but corresponding displacements were moderate due to the low density of the materials tested. The material cores were Coremat (a regular grid of obliquely assembled cell walls) and a honeycomb. Face sheets for the Coremat material were made of woven glass/ester laminates. Face sheets for the honeycomb sandwich material (the Aerolam panels) were made of glass/epoxy laminates. The sample panels were 50 x 50 cm in dimensions and they were tested statically and with the drop-weight machine. The tests demonstrated that energy absorption capacity increases with an increase of the impact energy. It was also shown that the core crush mechanism dominates in the energy absorption process and the perforation energy increases for the impact tests, when compared with the perforation energy for the static tests.

Damage patterns have been analysed in paper [Chung, 2002a]. In this study, an aluminium honeycomb material was loaded statically and at low velocities of impact. The tests were conducted under uniaxial and bi-axial loading conditions and in two loading directions with respect to the material symmetry axes. Small strains were not exceeded in these tests and these conditions kept the material below the compaction state. The study observed a uniform deformation initially during the testing and the collapse of cells according to several collapse patterns, depending on the pre-applied testing stress. Cell wall buckling observed in the tests is a usual micro-structural mechanism resulting in macroscopical deformation.

Morphological analysis of the damage mechanism for a number of foam materials has been reported in paper [Song, 2005a]. The damage process was associated with a phase transition process as a result of this analysis. In the first stage of the material compression (before the plateau stress response), the foam material studied exhibited a homogeneous deformation. During the second stage of compression (compaction), the deformation was essentially heterogeneous (microscopically) with high-density zones separated from low-density zones. Formation of high-density zones (regions subjected to buckling and loss of

stability between the cell walls) is controlled by a nucleation kinetic mechanism. The low-density zones are the primary ones for the first pre-compaction stage of compression. Major absorption of energy occurs during the second stage of compression and this state evolves according to nucleation and growth processes that are typical for a phase transition process. During the third stage of compression (densification) the high-density zones propagate through the whole volume of the material.

A DYNA-simulation of a honeycomb sandwich structure has been conducted in paper [Nguyen, 2005] in order to validate a numerical meshing approach where honeycomb and folded structures are represented by a finite-element model with the mesh generated by the Sandmesh pre-processor. The simulation described reasonably well the response of samples for two LVI events (with impact energy of 1 and 15J) and the residual damage. However, the load-time features, which were apparently associated with the damage of face sheets, were not captured, when modelling the LVI response of a F-111 aircraft panel. In paper [Kretz, 2002], a head injury criterion was considered as a measure of the absorption capacity of an aluminium foam material. This measure was selected to be a characteristic, which is proportional to an integral of acceleration when impacting a foam material target. This characteristic increases as the acceleration increases and the impactor-target contact time reduces. The optimisation recommendation was to select a foam material with a long plateau stress response part of the compression curve (a larger compaction capacity).

Several polymeric structural foams have been characterised in paper [Avalle, 2001], using low-velocity impact tests (the strain rate is approximately equal to 60 sec^{-1}). The test results have been compared with quasi-static tests at a strain rate of 0.02 sec^{-1} and hydraulic tests at 2 sec^{-1}. A concept of efficiency was developed which relates the absorbed energy to the peak stress achieved. Thus, at a given total energy applied to a volume of material the characteristic of efficiency takes the maximum value when the energy absorbed is large and the peak stress achieved is low. From the stress-strain response viewpoint it means that the best material for a specific application is one that absorbs bulk energy before the start of densification and at as low a plateau stress level as possible. The efficiency curves drawn against stress might be used for the optimisation of the design allowables. Such efficiency curves have been obtained in this study for expanded polypropylene, polyurethane, and polyamide foams. The polypropylene and polyamide foams demonstrated rate sensitivity, whereas the polyurethane foam, when failing during a large plastic deformation, showed no significant rate sensitivity. A long compaction plateau area was noticed for the polyurethane and polyamide foams, which explains their high efficiency under the present conceptual analysis.

5.3 Repeated low velocity impact and the pre-stress effect

Impact resistance is a characterisation of material response to a single impact. In contrast, the resistance of material to multiple impacts is not fully characterised by the impact resistance because after just the first impact the material properties of a target material may change significantly in the vicinity of the impact point. After the first impact, the

target material state may acquire micro-stresses and micro-damage, resulting in a pre-stress and/or pre-damage state. Therefore, generally speaking, the resistance of material to repeated impact is associated with both damage resistance and damage tolerance. For example, the number of impacts which can be tolerated by a sample, could be considered as a damage tolerance characteristic along with the CSAI (Compressive Strength After Impact).

When conducting repeated impact tests, the incident energy is frequently considered as the only relevant characteristic of the input energy deposited in a target. However, the LVI tests conducted in paper [Sugun, 2004] have demonstrated that this may only be true above an impact energy threshold. Below this energy threshold (for a glass/epoxy composite material tested in this paper the threshold was found to be near 8-10 J) the mass of the impactor might be relevant and a heavier impactor results in quicker failure of the sample.

The effects of repeated impact can be more important for the static load target response than for the target response to successive impact events. For example, in paper [Lagace, 1994] the effect of impact pre-damage is inspected by both static indentation and LVI response tests. In this study, a low-velocity impact (12J) generated a zone of delamination slightly more than 1 cm in diameter for a graphite/epoxy laminate. The targets were inspected by the two methods before impact (virgin target) and after impact (pre-damaged target). The force-time and displacement-time curves for the secondary high-velocity impact test showed almost no difference between the virgin and pre-damaged targets. The force-indentation curves obtained with the static indentation test demonstrated a difference in the response of almost 50% between the virgin and pre-damaged targets.

When the number of impacts increases the material response may become more complex. A study, which was conducted in paper [Baucom, 2005] for E-glass 2D, warp knit, and 3D-composite systems, considered multiple impact events performed with a drop-weight testing machine. In the analysis of this paper, the dissipated energy was evaluated as the difference between the impact and residual energies. With a low velocity of impact the residual velocity can hardly be measured, so the acceleration of the impactor was recorded and the increments of energy change could be obtained after integration of these records. After the first impact event, the energy dissipated during the second impact was not dependent on the first event. However, after multiple impacts, the energy dissipation increased and the peak force decreased with the number of calibrated impacts. However, the critical number of impacts, when the energy/force change was clearly seen, differed significantly with the material structure – this number was lowest for the 2D-system and highest for the 3D-system. The energy dissipation for the 3D-system was almost twice that of the 2D-system.

Repeated impact tests (the impact energy was approximately 7 J) against unidirectional, quasi-isotropic (cross-ply) and non-symmetric laminates (the target thickness was approximately 4 mm) have been reported in paper [De Morais, 2005]. An instrumented drop-weight machine was used in order to obtain load-deflection curves and these curves

were used for evaluation of the current stiffness. Deterioration of the stiffness and an increase of the contact indentor-target contact time (contact duration) was noticed as the number of impacts increased. The relationship of the contact duration to the number of impacts was fitted to a quadratic dependence, the coefficients of which were associated with: i) the degree of freedom of composite material to deform (a free term); ii) the rate of change of the composite properties with number of impacts (a linear coefficient); and iii) the change of the damage mechanism with the number of impacts. This experimental analysis [De Morais, 2005] observed the least resistance to the number of impacts for unidirectional laminates, for which cracks propagate along the fibre direction. The observation showed, as expected, a much better resistance for the cross-ply and non-symmetrical laminates. In these cases indentation developed gradually at the place of impact (a crack pattern along the fibre direction was noted only for the face laminates). Damage growth, which was associated with stiffness degradation, was found to increase linearly with the number of impacts for the unidirectional and cross-ply laminates and non-linearly for the non-symmetrical laminates. As a result, the non-linearity of the contact-duration – number-of-impacts dependence was substantiated by the possible variation of the damage mechanism.

Interrupted tensile tests have been reported in papers [Jendli, 2004; Jendli, 2005] for a glass/polyester composite. This technique allowed the authors to load the same sample at three different strain rates (approximately $2 \cdot 10^{-4}$, 8 and 20 sec^{-1}). A servo-hydraulic testing machine was used for the loading. Macroscopically, the damage degradation during a loading event was evaluated as a reduction of stiffness after the event. Microscopically, the damage measure was the percentage of debonded fibres counted from SEM observations. During the tensile tests, a lower damage accumulation and more delayed damage (the onset of the damage growth at a higher strain) were observed at higher strain rates, which was associated with the viscous nature of the composite material (in fact, the composite matrix).

Helicopter composite material components subject to impact threat are likely to be under a static load prior to impact. Therefore, evaluation of the impact resistance of a composite target under pre-stress is an extremely important field of testing studies. Arrangement of pre-stressed conditions is not an easy task and not many examples of such the evaluations are available. Impact tests of anvil-supported and free CFRP beams, which were impacted along the whole width of the beams by an impacting wedge (pendulum), have been reported in papers [Butcher, 1979; Butcher, 1981]. These papers observed that under pre-tension conditions, cracking started from the frontal surface of the beam target (the target's surface that is in contact with impactor). In contrast, impact against unstressed samples resulted in the successive in-plane delamination of the target beam ahead of the impacting wedge followed by impactor penetration and a through-thickness crack in the beam. For unsupported beams the fracture mode was usually tensile due to the pre-tension, except for the case of the thickest samples (see [Butcher, 1981]). The shape of the impactor is an essential factor contributing to the fracture mechanism in the pre-tensed samples.

The impact resistance of pre-tensed, pre-compressed and unloaded quasi-isotropic graphite/epoxy laminated samples have been studied in paper [Chiu, 1997a] with an instrumented drop-weight testing machine. The pre-load stress level was selected to be 20% of the ultimate compressive strength of the material. The peak load was recorded and C-scan inspection of the samples after impact was conducted. A peak load decrease was observed in the following test set-up sequence: i) pre-tensed, ii) unloaded, and iii) pre-compressed. However, the damage area exhibited a rather different trend. The damage was minimal for the unloaded samples. The damage area was larger for the pre-compressed samples and the major axis of the damage zone ellipse was aligned with the pre-compression direction. Finally, the damage was largest for the pre-tensed samples, where the major axis of the damage zone ellipse was perpendicular to the pre-tension direction.

The simple stress state in the pre-loaded sample considered in [Chiu, 1997a] is a simplification of the actual pre-load occurring in helicopter composite components. Bi-axially pre-loaded samples have been tested under LVI conditions in paper [Whittingham, 2004]. The samples were made from a graphite/epoxy composite. Two perpendicularly acting hydraulic rams with a loading capacity up to 500kN were used for pre-stressing. The pre-stress states introduced in these tests were: i) 0; ii) uniaxial tension with 1000 με-pre-straining (1000 microstrains (με) correspond to the 0.1% of the tensile deformation) and 1500 με-pre-straining; iii) bi-axial tension-tension pre-straining under 500 με-500 με and 1000 με-1000 με; and iv) bi-axial tension-compression (shear) pre-straining under 500 με-500 με, 1000 με-1000 με, and 1500 με-1500 με. The uni-axially loaded samples were impacted with an impact energy of 6 J and the samples from the remaining set-ups with energies of 6 and 10 J. The load-time curves that were recorded by the instrumented testing machine and the absorbed energy (which was assessed from the impact and rebound velocities) do not show any significant difference in impact resistances for the unstressed and pre-stressed cases in this study.

Another study published in paper [Robb, 1995] noted that there is no significant damage growth in GRP samples up to the pre-strain level of ±2000 με. This study was conducted with a calibrated constant level of impact energy (21.5 J), using a drop-weight testing machine. However, the test results indicate a significant difference at a pre-strain of the order of 6000 με. This study reported a minimal absorbed energy E_a at the (+6000 με, +6000 με) – pre-strain, and a maximal E_a at the (+6000 με, –6000 με) – and (–6000 με, +6000 με) – pre-strain; slightly less E_a than that under the shear pre-stress was observed at the (–6000 με, –6000 με) – pre-strain. Within this LVI testing series, the peak force taken by the facility instrumentation exhibited an opposite trend. When inspecting the samples after impact, the damage area exhibited a clear maximum at the (+6000 με, –6000 με) – and (–6000 με, +6000 με) – pre-strain (shear). This maximal damage area exceeded the damage areas for the remaining cases by almost 140%. It is interesting to note that there was no direct correlation observed between the absorbed energy and the damage area. Micro-mechanical modes of failure were believed to be responsible for this lack of correlation.

Complex stress states are common in the composite material of air-structure skins and other components. Generally, the complex stress state developed at impact may significantly complicate the impact response of composite targets. For example, if normally (at a simple stress state) the peak stress achieved at impact increases with the strain rate, the in-plane loading of a sandwich structure may produce the opposite effect. Results of quasi-static in-plane compression tests on sandwich samples at different rates have been reported in paper [Sharma, 2004b]. The results showed a decrease of the peak stress with strain rate increase. However, in accordance with the general trend, stitching of the sandwich structure increased the peak stress. The peak stress increased even more when reducing the stitch spacing (the increase of the resistance to LVI delamination with stitching density has also been modelled by FEM simulation in paper [Chen, 2004b]).

5.4 Influence of external boundary conditions

Under LVI and static test conditions damage spreads over a quite wide area, whereas under high-velocity impact conditions impact damage is highly localised in the vicinity of the impact zone. Therefore, the boundary conditions may play a significant role in the LVI response of a target, depending on the projectile-target contact duration. An example of the vibration response for different boundary conditions has been investigated by Fourier series analysis in paper [Khalili, 2005]. In particular, the plate response was found to be quite sensitive to fibre orientation in the target material for non-symmetrical arrangement conditions of a composite plate subject to a vibration load (an example of the non-symmetrical arrangement is the clamping of the target at two sides and leaving two other sides free). In contrast, the vibration response was found to be more tolerant to the fibre orientation in a composite plate for symmetrical conditions in a target set-up (regardless of the type of the boundary conditions: clamping, free ends, or a simple support, it is important that identical conditions be present on all four sides of the target).

A parametric study of boundary condition effects on the strain that is achieved during impact has been conducted in paper [Prasad, 1994]. This study analysed the response of composite targets to low-velocity impact. Gas-gun shots and drop-weight impacts (1-6J) were carried out in the experimental section of this study. The composite specimens were 12.7 x 25.4 cm in dimensions. Projectiles used in the gas gun tests were 1.27 cm aluminium or steel balls. The drop-weight impactor had a tup of approximately the same size and the weight of the impactor was 1.18 kg. An analytical technique employed in the theoretical section of the paper is based on a plate theory that takes first order shear deformation effects into account. Results of the parametric study, which were confirmed by the calculations, demonstrated that boundary conditions are more important for the conditions of the drop-weight tests than for the gas gun experiments. It can be noted that a simple evaluation of the duration of the impact process could lead to the same conclusion. It is obvious that the projectile-target interaction time is much smaller for the gas gun tests than for the LVI tests and this allows the boundary conditions to be neglected for samples of this size in the case of the gas gun testing.

The influence of boundary conditions can also be investigated by testing beam samples of different span sizes. The general rule, when testing beam samples, is that increasing the target span means reducing the shear mode of deformation under LVI. Damage patterns and contact forces have been reported in paper [Cho, 2002] with instrumented LVI tests and FEM modelling. Results of the 2D FEM calculations (this numerical analysis neglected stress distribution through the sample thickness) have been compared with the results of 3D calculations and experiments. This comparison enabled the authors to claim that a span-to-thickness ratio more than 30 is a fair criterion for the use of the 2D FEM approach. Literature on the sample span influence on the damage mechanism in the target material has also been reviewed in subsection 5.1. The study in the paper [Cantwell, 1990] (reviewed in subsection 5.1) considered a number of LVI tests varying the length of a beam and keeping width and thickness constant. The perforation energy results for these tests allowed the authors to conclude that the LVI resistance of a composite structure is determined by its geometry and configuration. Therefore, the LVI response of scaled laboratory-type samples may not reflect the response of a full-scale structure.

Scaling effects which are associated with the sample diameter, have been analysed in paper [Sutherland, 2005b]. The samples were low-fibre E-glass composite targets under LVI testing with a drop-weight testing machine. The samples were clamped at 50 and 100 mm-diameter openings and impacted by head tups of 10 and 20 mm in diameter, respectively. The diameter-to-thickness ratio of the target samples was one of the parameters involved in the analysis. Thus, the sample thicknesses were varied from approximately 2 to 10 mm for the small diameter samples and from 3 to 12 mm for the large diameter samples. The impact energies were also varied with the sample size, according to the quadratic law (see papers [Sutherland, 2004; Sutherland, 2005a] of the same authors reviewed in subsection 5.1). This means that the impact energy was varied from 0 to 70-100 J for the small samples and up to 250 J for the large samples. Force-time and force-deflection curves and the impact durations were recorded during the instrumented tests. From the data obtained, the damage mechanisms seemed to be quite diverse and the results did not show a straightforward scalability. The maximum force-impact energy relation follows the same abovementioned quadratic law, which was reported earlier by the same authors (see, e.g., [Sutherland, 2004]). For thin samples, the contact duration initially decreases with increasing impact energy; this initial effect is attributed to strain rate effects. A change of the damage mechanisms (bending rather than shear) is associated with the thickness-to-diameter ratio, the diameter of the head tup, and the incident energy of impactor.

Numerical analysis of the influence of the plate's aspect ratio α (that is the plate's diameter over its thickness) on the failure mechanisms has been conducted in paper [Fatt, 2004]. Failure occurred with a low-velocity impact against a cross-ply laminate target (the plate's boundary condition was the clamping). The analysis for three aspect ratios revealed that for thin targets ($\alpha = 50$) the plate was under large bending deformations (the membrane phase) before target failure occurred with the fibre breakage at tension. From the modelling viewpoint, the paper has concluded that the plate failure at $\alpha = 25$ could be predicted with models of progressive failure (the ply-by-ply failure mechanism), using

failure criteria of the stress envelope type (phenomenological criteria declaring failure when stress has achieved a critical surface in the stress space). For thick targets ($\alpha = 12.5$), the plate response combines the indentation (a local deformation in the vicinity of the indentor, so the analysis had to take into account the through-the-thickness distribution of parameters) and the plate deflection (the shear deformation mode). Most of the energy was absorbed through delamination and deformation except for the case of the thickest targets, where the equal contributors are the energies absorbed at deformation and fracture (due to shear).

Edge boundary conditions, when the target's surfaces are assumed to be free, are not the only conditions affecting the impact resistance of composites. Conditions at the target surfaces are important too. For example, the study [Butcher, 1979] that was mentioned in the preceding subsection considered pre-tensed CFRP anvil-supported samples loaded by an impacting wedge (thus, one surface of the target was in contact with the anvil). The paper analysed pre-tensed and unstressed samples. It was observed that in the pre-tension conditions cracking starts from the surface of impact. In contrast, in the unstressed condition a compression zone is formed ahead of the impactor and the tensile zone is formed at the distal side of the target, where the crack is likely to start. In the case of a supported sample there is no compression that is usually associated with bending of the sample. As a result, compression fracture cannot be achieved and for the pre-tensed samples the fracture mode is tensile. The unsupported specimens had less delamination after impact than the supported ones indicating that the unsupported samples can better withstand impact due to the flexure (see [Butcher, 1979; Butcher, 1981]). The conclusions of the study [Butcher, 1979] were that cracking from a compact impactor is unlikely to spread sideways (perpendicular to the pre-tension direction) and that the shape of the impactor plays an important role in selection of the fracture mechanism.

In paper [Found, 2004], static and drop-weight tests of quasi-isotropic CFRP panels, whose structure was varied with different types of fibre and matrix, have been reported. Target damage was assessed with X-radiography. The test results showed better energy absorption for larger (300 x 300 mm) targets, when compared with 100 x 100 mm targets. Paper [Duan, 2005b] studied numerically how the boundary effects of a composite target influence the absorbed energy. This study dealt with ballistic impact (at relatively low velocities of impact) against a low stiffness fabric. The numerical simulations of target behaviour at impact analysed the following two cases: i) the target edges were clamped around all four sides (the symmetrical case); and ii) two opposite sides of the target were clamped and two other sides were free (the asymmetrical case). This numerical analysis showed that energy absorption is more significant in the asymmetrical case. Even more energy was absorbed when all the target sides were free because these boundary conditions increase the influence of the projectile-target friction effect (see paper [Duan, 2005a]).

Material structure may play a significant role in material resistance if the sample's boundaries are involved in the deformation process. For example, deformation of samples made of a cellular material has been considered in the paper [Baker, 1998]. Crushing of the

material cells due to buckling started initially from unconfined cells at the free boundary of the sample tested. As a result, the specimen's size affected the collapse process. In this work [Baker, 1998], a special design of the sample's lateral constraint (a boundary limiting assembly composed of space-separated constraining rings) has been used in order to minimize the sample size effect. This design was successful only for the deformation of aluminium honeycomb material where the constraint promoted a local buckling mode inside the sample, which allowed the authors to suggest that the stress activating this mode is a material characteristic regardless of the sample size. Stainless steel honeycomb material was tested with the use of another boundary arrangement. A solid tube constrained the material sample in order to minimize the boundary effect. It should be noted that the solid tube constraint imposes specific boundary effects, which may have to be analysed as well. It should also be noted that the cell size and cell wall thickness (as well as the cell material strength) is smaller for the aluminium honeycomb material studied in this paper [Baker, 1998] than for the stainless steel honeycomb material. These material structure variations might explain why the constraint design, which was successful when testing the aluminium honeycomb material, could not be used for testing the stainless steel honeycomb material.

The impactor (e.g., a head tup of a drop-weight machine for LVI tests) can be also considered as an external boundary condition which affects a target's damage resistance via the impactor's shape. The impactor shape effect, which is extensively discussed in the analysis of results of ballistic tests, is frequently ignored in the case of LVI tests (the LVI test results are predominantly concentrating on the target material behaviour). Nevertheless, several publications analyse impactor shape effects. For example, a study conducted in paper [Mitrevski, 2005] considered drop-weight testing of woven carbon/epoxy laminates with impactors having hemi-spherical, ogival, and conical head tups. The peak load, the absorbed energy, and the damage area (assessed with C-scanning and thermograph inspections) were traced during impact by these impactors. The maximum peak load was recorded for the case of a hemi-spherical impactor and the maximum absorbed energy (which was calculated from the difference of kinetic energies based on the impact and rebound velocities) was reported for the case of conical impactor. The damage area was slightly larger for the case of the hemi-spherical impactor followed by the conical, and then by the ogival impactors and different damage mechanisms were clearly dependent on the impactor's shape. As could be expected, the damage mechanism of the target material for the impact by the hemi-spherical tup was mainly matrix cracking. For the case of the conical impactor the prevailing damage mechanism was fibre breakage and an intermediate situation was reported for the ogival impactor, where the damage mechanism was a mix of the above-mentioned damage modes.

5.5 Manufacturing, structural and environmental conditions

Low-velocity impact tests have been typically conducted for composite plain coupons (composite laminate plates). The boundary conditions of the plate samples do not represent the whole range of the restrictions under which a material might be tested. For example, a material's structural features with respect to a specific point of the load

application could be of importance for the response of the composite material subject to impact. An example of such a study has been published in paper [Kim, 2004a], where a part of a drive shaft in the form of a structural element (hybrid composite/aluminium cylinder) has been tested with an instrumented drop weight machine followed by damage resistance analysis. Recommendations on the stacking and hybridisation sequence in order to maximise the resistance have been suggested in this study.

The influence of sequence combinations of a hybrid material on the impact resistance is an intriguing aspect in the attempt to improve the resistance and, simultaneously, to maintain the areal density of a hybrid composite assembly. Study [Hosur, 2005b] considered the LVI response of a carbon/epoxy (CE) composite, an S2-glass/epoxy composite, and several hybrid combinations of these two materials, while keeping the areal density approximately constant. The peak load and absorbed energy, which is assessed as the difference between the total energy and the energy obtained by integration of the load-deflection dependence up to the peak load, were measured and compared for those hybrid materials for impact energies from 10 to 40 J. The study demonstrated a slight increase in the peak load for the CE composite and a strong increase in the peak load for the remaining assemblies. The CE composite showed a large increase in the absorbed energy compared with a linear moderate increase for the other hybrid materials. Using the damage assessed and the load-deflection responses recorded, the study concluded that hybrid materials with layers of glass/epoxy composite at the front and rear sides and a centred CE layer provided an increase in damage resistance and damage tolerance, when compared with a target made of pure CE composite material (as is widely used in the aerospace industry).

Hybrid material variations can be performed at the meso-structural level. However, damage due to impact occurs on the microstructural level. Therefore, the best performance of a material to specified loads can be better achieved when modifying the material structure during composite manufacture. Thus, variations in the material design on the micro-level, which are associated with manufacturing, modifications of the structure, constituents, and the constituent's mechanical properties, are of major interest to researchers when studying impact response and the influence of environmental factors on the response.

In the paper [Dost, 1991], the influence of the stacking sequence on a Characteristic Damage State (CDS), which is actually treated in this work as the delamination state of the material (see subsection 5.1, regarding this CDS definition), has been studied experimentally. Non-instrumented drop-weight impact was the cause of damage to the carbon/epoxy targets and the impact energy of the drop-weight varied from approximately 5 to 65 J. The material was based on quasi-isotropic lay-ups with seven stacking sequences, which varied from a homogeneous lay-up with a 30°-fibre-direction ply-to-ply variation to a heterogeneous lay-up with 45°–fibre-direction ply-to-ply variation and an increased ply group thickness (several plies of the same fibre orientation in a set). A typical laminate contained 24 plies in total (with one exception for a material that had 32 plies). The thickness of each ply varied from 0.15 to 0.193 mm, resulting in target thickness

from approximately 3.5 to 5 mm. Formation of the sublaminates (several laminates separated by delamination zones) during impact was one of the key processes pointed out in the paper. It was claimed that the sublaminates control the CAI tests and affect predominantly the CSAI. Therefore, the stacking sequence was believed to be the main parameter controlling the CDS that is affected by the sublaminate thickness. Symmetric damage is most desirable for the post-impact analysis and construction of an analytical tool but it was recognised that the CDS is mainly asymmetric with a higher concentration of damage at the distal side of the target, where the damage includes both delamination and fibre breakage. The trend observed was that brittle composite materials are likely to have a symmetric CDS and the delamination resistant materials an asymmetric CDS. Thin laminates and materials with heterogeneous stacking sequences also tend to have an asymmetric CDS due to LVI. This damage state is characterised by a higher concentration of damage at the distal side of the material target. For very thick laminate targets, the CDS is asymmetric too, however, the CDS is characterised by extensive damage observed at the impact side of the target. It was found, using C-scanning inspection, that the ratios of the delamination areas at each ply interface to the total delamination area (a sum of the areas at all interfaces) are nearly independent of the impact energy. These ratios are determined by the boundary conditions and the stacking sequence. Nevertheless, the total damage area increased with an increase in the impact energy. The delamination size at a ply increased with an increase of the depth of the ply in the target, having the smallest delamination area for the ply closest to the impact surface of target.

Paper [Liu, 2000] describes the testing of targets made of a glass/epoxy laminate (0/90 lay-up) and an epoxy resin. The laminate thickness was 3.2 mm and the dimensions - 12.5 x 10 cm (the target area subject to impact was 10 x 7.5 cm). A drop-weight testing machine was used with the impact velocity of the drop-weight up to 8 m/s and the impact energy level up to 200 J. Two-plate assemblies were studied, which were joined by: i) adhesive bonding; ii) mechanical fastening; and iii) stitching. From the graph of the absorbed energy versus the impact energy, the threshold where the impact and absorbed energies are nearly equal to each other was called the penetration energy. At a higher impact energy E_p, the absorbed energy did not change significantly with further increase of the impact energy and this level E_p was called the perforation energy. The difference between the perforation energy and the penetration energy was found to increase with the target's thickness. The comparison of the test results for the materials composed by various joining methods showed that the most efficient joining technique, which resulted in the highest energy absorption, was adhesive joining. The perforation threshold E_p increased with the bending stiffness, so one of the most efficient ways to increase the energy absorption is to increase the target's thickness. This can be further improved by the appropriate selection of the joining technique. From the study [Liu, 2000], it was concluded that the assembled plates have comparable bending stiffness and perforation threshold E_p characteristics, when compared with homogeneous laminates of the same thickness.

Composite response to low-velocity impact is also affected by the reinforcement effect, which was observed for ballistic impact reviewed in subsection 4.3. For example, an investigation of the response of E-glass 2D and 3D-systems to LVI has been conducted in

paper [Baucom, 2005] where the LVI event was realised with 2 m/s velocity and 18 J impact energy. The study demonstrated large damage areas and the energy dissipation for the 3D composite systems. This damage behaviour was associated with energy redistribution over a wider area due to straining and fracture of the z-tows. Stitching plays an important role in reduction of the impact resistance. A study has been conducted in paper [Velmurugan, 2004] on the response of samples that are composite tubes made from fibre-reinforced plastics. The samples have been tested statically (tensile tests) and dynamically (Izod impact test) showing that stitching improved significantly the delamination resistance and the energy absorption capability. It should be noted, at the same time, that the tensile and bending properties degraded due to the stitching. The stitching factor was analysed in papers [Hosur, 2003b; Hosur, 2004c] which considered a glass/epoxy composite subject to LVI testing. The test results were presented as absorbed energy versus impact energy and demonstrated a higher absorbed energy for targets with stitching because of the damage spread through the thickness. On the other side, the damage area assessed with C-scanning inspection was larger for the unstitched samples because of the in-plane damage spread. In these studies, for the stitched samples, the stiffness decreased and the peak load increased (but not very significantly), when compared with the unstitched samples. The peak load for the stitched material ultimately decreased at energies close to the penetration energy. The delamination damage was very limited for stitched samples since indentation and penetration are the predominant modes of fracture.

The fibre content can also be considered as a reinforcement factor. For example, the influence of this factor on impact and compression strengths has been studied in paper [John, 2004]. In this study it was found that the impact strength of a glass-sisal/epoxy composite (Izod tests) increased with an increase in the fibre content. However, the compression strength decreased with an increase of the fibre content, which effect was attributed to poor adhesive fibre-matrix contact (the strength increased after fibre surface treatment).

The fibre transfer load in composites, which is associated with the quality and choice of fibres, is a very important factor in the impact resistance of composites. Impact testing (Izod tests) of two composite systems has been conducted in paper [Hassan, 2004]. Two glass/epoxy composite systems were tested in this study. The fibres in these systems were randomly oriented with two average lengths of the fibres for each of the two composites (fibres less than 1 mm were constituents of the short fibre system and fibres of the order of 3-6 mm for the long fibre system). The test results demonstrated an increased static tensile strength and energy release rate under impact conditions for the long fibre system, when compared with the short fibre system (while keeping the same fibre concentration).

The special treatment of fibres may improve the impact properties of a composite in normal conditions but the same treatment may reduce impact resistance in a harsh environment. For example, alkali treatment of natural fibres (jute) varies the defect concentration in the fibres. It has been found in paper [Sarkar, 2004] that the fatigue resistance under Charpy test conditions is significantly dependent on the defect

concentration. The defect concentration was reduced after 4-hours treatment but increased and even exceeded the initial concentration after 8-hours of treatment. The elastic modulii and flexural strength showed an inverse dependence on the fibre treatment time. The impact resistance correlated with defect concentration at normal temperatures and an inverse correlation was observed at low temperatures. This resistance dependence has been explained in this study [Sarkar, 2004] by the influence of the stress concentrators that were caused by the expansion of ice which solidified from moisture in the defect vicinity at low temperatures.

Epoxy resin is the most frequently used matrix in composite materials, but it is brittle when dried out. An attempt to use polymeric blends and additives that increase the viscosity of the matrix has been considered in paper [Antonov, 2003]. This study demonstrated that the fracture toughness at LVI and the total absorbed energy (the total energy minus the elastic part that was obtained by the integration of the load-deflection curve up to the maximum load) increased with the introduction of matrix modifications. The rate of energy absorption versus strain rate within the loading range considered in this paper also increased. Another method to modify the matrix is to increase the porosity of the matrix, which was considered in paper [Baucom, 2004]. In this case, the load-deflection response at LVI did not exhibit a sudden drop, corresponding to failure, which is typical for composites with nonporous matrices. A gradual decrease in the force response was observed, which was linked with pore collapse. The energy absorption capacity was observed to be higher for such a composite system, even if the peak load was almost 50% less than for the case of a nonporous matrix. As a bonus it should be noted that a weight saving is achieved for the porous matrix systems.

Environmental factors are not as important in the LVI range as in the ballistic velocity range. However, the temperature factor can play a role. Impact resistance was studied in paper [Zimmerman, 1987] for three fibre systems (Kevlar, E-Glass, and Spectra polyethylene fibres) and two matrices (a Shell Epoxy and a vinyl ester resin), which comprised cross-ply laminates and fabrics. Low velocity/high energy (up to 160J) testing was performed with a drop-weight testing machine at three temperatures (-50, 23, and 100°C). The test results showed slightly higher temperature dependence for the Spectra composite systems than for the Kevlar and E-Glass composites. The lowest impact damage (determined by the size of the delamination zone) and the highest energy absorption were observed in the Spectra systems.

Four types of CFRP laminates (unidirectional, cross-ply, quasi-isotropic, and woven) were tested under LVI conditions in paper [Gómez-del Río, 2005b]. A drop-weight instrumented machine with the load cell used for both force and displacement recording was employed for the testing. A climatic chamber was arranged for the tests at temperatures of 20, –60, and –150° C. The impact energies between the damage threshold and the perforation level were selected for these four composites. C-scanning inspection was used for assessment of the damage extent (the delamination area). Dependencies of the absorbed energy versus the impact energy do not exhibit a significant sensitivity to temperature *T*. The damage extent at the impact side of the composite targets also did not

show a significant effect with *T*. However, the damage extent at the rear surface of the target increased as the temperature decreased. The damage increase was observed at all impact energies and composite structures. Thus, the greater extent of damage, when lowering *T*, was not accompanied by energy dissipation. This change in the damage character at low temperatures was explained by embrittlement of the composite constituents at extremely low temperatures. In contrary, an absorbed energy increase has been observed in paper [Kalthoff, 2004], when the temperature increased above the normal level (up to 150°C). Charpy tests on glass/vinyl ester laminates were conducted in this study.

The influence of moisture content on impact resistance has been studied in paper [Imielińska, 2004] for a hybrid aramid-glass-fibre fabric and a material that was composed of an aramid-fibre fabric with glass-fibre interlayers. Dry and water-saturated samples were subject to LVI tests (the energy of impact varied from 0 to 32J) with an instrumented drop-weight machine (the load and displacement were recorded independently). The load-deflection response demonstrated the highest peak load for the 'dry' hybrid fabric (a 20% increase, when compared with the remaining composite systems) and very similar responses for the 'dry' interlayer and the 'wet' (both hybrid and interlayer) samples. The energy absorption was slightly less for this three-composites group of samples. The damage area was larger for the interlayer structure and the 'wet' samples (at the maximal impact energy of 32J in this group of tests); however, this damage area increase was not consistent with the results for the lower impact energies. The damage mechanisms observed were typically delamination at the impact side of target, matrix cracking and fibre-matrix debonding at the distal side of the target.

5.6 Numerical techniques. Damage modelling

There is no a widely accepted parameter that controls the damage level, and such universal parameters probably do not exist. Existing damage parameters are frequently associated with a specified mode of damage. The most accepted approach is to associate the damage extent with the degradation of the elastic modulii. A simple model has been suggested in paper [Chen, 2004c] for the delamination analysis of composite laminates under vibration. The model is a step-wise degradation of the elastic modulii at the fulfilment of a damage criterion (for this instance, the Young modulus was degraded by 44% when the damage had occurred). In this study, the damage was assumed when stresses in the composite material reached a limiting stress taken from an envelope surface in the stress space. This ultimate simplification of the fracture description in composites is routinely used when modelling the composite behaviour with hydrocodes (see, e.g., description of several material models for composites from the DYNA material model database [LS-DYNA Manual, 1999]). With this simplification, fracture onset starts with similar fracture criteria in the same manner as the yield stress limit is obtained for anisotropic plastic materials (see [Matzenmiller, 1991]). Similarly, the failure of fibres and matrix can be incorporated in models of this family described in papers [Chang, 1987a; Chang, 1987b; Goldberg, 2002], if macro-mechanical considerations are involved in the model design.

Structural constituents of composites may also be involved in the fracture analysis within a similar approach. For example, the fibre orientation in individual plies that comprise a laminate has been taken into account in a study [McCartney, 2005]. A simple facture model was suggested in paper [De Moura, 2004]. The model employs a piecewise linear stress-strain diagram with an elastic branch at small deformations followed by linear softening (a bi-linear stiffness model). The softening slope and associated crack displacement have been determined from experimentally obtained critical fracture energy (an integral of the stress response over strain). This technique could be specified for different fracture modes. In fact, the modelling in this study used the respective critical energies and simulated the crack opening of samples subject to LVI for specified unmixed fracture modes, using the ABAQUS code. It should be noted that the delamination size obtained with this numerical simulation disagrees with experimental results, probably, because of mixed fracture modes occurring in the real experiments. A similar modelling technique based on DYNA FEM code, used for simulation of the delamination, was reviewed in paper [Elder, 2004]. Using this approach, possible mixed fracture modes could be considered with a fracture toughness envelope applied when fracture occurs if the energy release rate approaches a critical value – the fracture toughness (a critical surface is the fracture criterion that is considered for the fracture energies in the energy-release-rate space, the principal directions of which are associated with different pure fracture modes).

Another simplified approach has been suggested in the paper [Zachariev, 2004], which directly connected a damage distribution with applied load (for a discussion on the loading parameter F/F_B used within this approach, see subsection 5.1). It should be noted that this is a typical static approach because it does not take into account the kinetic nature of the damage accumulation in a composite with the polymeric matrix (such material was analysed in this study).

Evaluation of damage due to low-velocity impact is frequently based on simple approximations of the load due to the impactor. For example, paper [Greszczuk, 1975] conducted an analytical consideration of low-velocity impact against composite targets. The behaviour of the composite material was approximated by anisotropic elasticity followed by instant fracture. It was found in this paper that the impact resistance increases with an increase of the material strength and a decrease of the elasticity modulii. The impact resistance was dependent on the elastic and strength properties in the in-plane and transverse directions. Paper [Sun, 1977] suggested a simple method for assessment of the absorbed vibration energy in a composite target. The model was aimed at the evaluation of impact damage to fan blades. The material model used in this method was based on linear anisotropic elasticity up to the material strength point. After approaching this point, the stress was forced to drop down to zero. The absorbed energy was related to the residual strength. A shear damage parameter was considered in paper [Papadakis, 2004b]. In this paper, the magnitude of this damage parameter was linked with shear damage degradation in a composite material. In this case, shear damage was associated with the shear-mode energy release rate (similarly to the energy release rate at the crack

propagation in a brittle material, which is associated with the brittle damage; in that case the energy release rate is considered as the rate of the energy change with crack length).

In composites with either a polymeric or other viscous matrix, damage may occur under a viscous damage mechanism, which progresses through damage accumulation. Typically, damage accumulation is sensitive to the strain rate. Paper [Papadakis, 2004b] analysed damage accumulation within the viscous damage approach and observed an initial decrease of damage followed by an increase along with a strain rate increase. This effect could probably be caused by the single shear mode of damage taken into account in the model, whereas experimental data on damage could actually involve a variety of damage modes.

An empirical constitutive model for the description of damage in a composite material has been outlined in paper [Song, 2003]. This model reduces the uniaxial stress that would occur under material deformation of a hypothetical undamaged material (the solid-state stress) to an effective stress that occurs in a damaging material (the actual stress). The stress reduction was performed by a scalar damage parameter, invoking Hooke's law. This model, in fact, might be reformulated through the introduction of the deterioration law for the elasticity modulii. The damage parameter in this model evolves according to a semi-empirical equation that relates the rate of change of this parameter with the stress and strain states of the composite. This family of models, in which the damage parameter evolves with load, has originated from the idea of nucleation and growth of the damage domains. Seaman, Curran, and Shockey (see, e.g., [Curran, 1987]) have this idea for modelling viscous fracture in ductile materials. A generalization of this idea for several mechanisms of damage (delamination, matrix cracking and fibre breakage in selected directions), which occur in composite fabrics, has been suggested in paper [Dechaene, 2002]. However, the degradation rule for elastic modulii and the damage parameter rates are of a purely fitting nature and they are unlikely to be associated with the physics of the phenomenon. An extension of the principle of stress/strain reduction from the scalar case (the scalar damage parameter) to the tensorial case (a damage-parameter tensor that has a potential to describe the complex-stress-state loading) has been conducted in paper [Guan, 2002]. The failure criterion used with this generalisation could, however, be applicable only to static loads (a stress envelope in the stress space is the failure criterion). Nevertheless, this approach allowed the authors to successfully describe the LVI response data of a composite (the load-deflection curves).

Constitutive modelling involves consideration of damage that is usually not well defined. For example, the abovementioned simple model developed in the paper [De Moura, 2004] described damage as a degradation of the elastic modulii. Similarly, a degradation rule for elastic modulii could be introduced substantiating the degradation by physical factors other than the damage (e.g., degradation due to the fire effect has been considered in paper [Asaro, 2005]). The same idea could be used for development of a model that describes the evolution of such a damage parameter. A damage tensor was introduced in paper [Edlund, 2004]. In this study, the constitutive equations for components of the tensor were derived from thermodynamics principles (similar derivations are usually

conducted in plasticity theories that involve the free energy potential). Anisotropic plasticity was a basis for the description of the behaviour of composite plies, when designing the model [Edlund, 2004]. Damage surfaces, similar to yield surfaces in plasticity theories, were fitted to the uni-axial experimental data. Similar data were also used for verification of the model. It should be noted that the same type of data was used for both the derivation and verification of the model, which significantly limits the applicability of the model. A model developed in paper [Luo, 2005] used a damage criterion that has an incremental nature. However, this criterion is not reduced to a fracture criterion, declaring fracture with reaching a critical stress. In this study, this is a constitutive model because the critical state that results in damage is determined by a number of evolution parameters. A damage parameter introduced in paper [Lene, 1986] can be responsive either to the porosity content (the viscous damage in matrix) or to slippage (the loss of cohesion between the fibres in matrix and between the fibre and matrix). Several simple examples shown in the paper [Lene, 1986] have demonstrated a possible applicability of the model to the description of elastic modulus degradation and the accumulation of residual strain under cyclic loading. Constitutive equations of a general form for the evolutionary damage parameter were used in this paper. These equations were complemented by the definition of generalised thermodynamic force as a derivative of the free energy over the damage parameter (the free energy was pre-determined). It should be noted that only elastic deformations were considered within this formulation.

The use of thermodynamics formalism is presently a common practice (see the detailed review of the relevant references in subsection 4.3). When using this formalism, introduction of the damage parameter in a set of thermodynamical variables results in the appearance of relevant thermodynamic forces Y (derivatives of the free energy over damage parameter). Paper [Barbero, 2005] has demonstrated how a complex constitutive model with an evolution damage parameter could be linked with a simple fracture criterion that is fulfilled at a critical stress. In this paper, the condition of the forces Y to reach the failure envelope in the Y-space is the fracture criterion and the forces and stresses are linked algebraically. In paper [Luo, 2005], similar thermodynamic forces are called the phase damage energy release rate (similar to the fracture energy release rate that can be calculated as a derivative of the internal energy over the crack length). How different damage modes could be involved in progressive damage has been shown in paper [Basu, 2003], which designed a relevant model.

A model that employs the thermodynamics approach has been formulated in paper [Jiang, 2004]. This model was used for FEM-modelling of the LVI response of a composite material. A feature of the model is the definition of a damage threshold which reduces the 'undamaged' strains to the actual strains (similar to the above mentioned principle of stress/strain reduction). However, the threshold damage surface has not been constructed even for a single simple case. The modelling results have just been compared between the case of undamaged laminate target and the case of a target with degraded elastic properties, without any indication of the extent of degradation. The conclusion of the study based on this comparison is obvious: damage reduces internal stress concentration.

A further development of this model has been conducted in paper [Jiang, 2004]. Pre-given damage threshold limiters were used for specified loading directions, when a laminate was subject to low-velocity impact by a ball projectile. The influence of the limiters on simulated composite response has been established (the critical values of the limiters, after which the damage thresholds have no further influence on the results, have also been established). An experimental verification has not been conducted due to the lack of data.

A damage parameter can be introduced directly in a model, as a characteristic of the damage, in contrast to the above-mentioned characteristic of the elastic modulii's degradation. For example, a damage parameter could be defined as the volumetric concentration of a completely damaged material (material that has the prescribed properties of the hypothetical damaged material) in a representative volume that may contain both the damaged and virgin materials (see [Resnyansky, 2003]). Virgin material is a material having the mechanical properties of solid (undamaged) material. It should be noted that the damage parameter in this model could be introduced in an alternative way, as a measure of softening (degradation) of the elastic modulii and strengths.

Damage and fracture could be calculated on the meso-level with the help of an explicit analysis of the inclusion-matrix interaction. Alternatively, the damage accumulation can be considered on the continuum level as a distribution/concentration (a continuum measure) of the inclusion-matrix delamination/debonding, the fracture of constituents, etc. The most straightforward way of validating the continuum models is the use of non-destructive inspection (see subsection 3.6). Transformation analysis has been employed in paper [Bahei-El-Din, 2004]. Using this analysis for 2D- and 3D-composites, the overall strain and stress were associated with local stresses and strains within a representative volume, embracing a cell of the periodic composite structures. Therefore, this approach has actually linked the micro-state (the meso-state, to be exact) with the macro-states (the phenomenological response of the materials), using transformation analysis, the main elements of which – the transformation matrices – have been generated during an FEM calculation. When evaluating a micro-state in a composite from its phenomenological state, the micro-state could be used for assessment of the damage state of the material. Several damage mechanisms have been incorporated into this assesment [Bahei-El-Din, 2004], including matrix damage (a softening law implemented in the stress-strain response was a realisation of this mechanism), fibre interface splitting, delamination, fibre breakage, etc. An advantage of this approach is the evaluation of the structure integrity at a low structural level, which includes yarn, lamina, fibres, matrix, etc. A lower structural level can be reached when increasing the number of the representative-volume elements (RVE). A disadvantage of this approach is the dependence of this RVE number on the finite-element (FE) solution. The numerical mesh-dependence of the analysis for the FE realisation should be noted too.

Paper [Resnyansky, 1997b] reports on the response of thick and thin composite laminates to a low-velocity impact in a three-point bending set-up with clamped edge samples. The loading direction was normal to the sample's surface and the laminate material symmetry axis was either aligned with the loading direction or off-axis. The model [Resnyansky,

1997a] that was outlined in subsection 4.2 has been employed for the modelling of the response. The model takes into account the micro-stresses developed during bending. With this simulation, the onset of damage started at the outer layers of the target opposite to the impact point in thin composite samples. In contrast, fracture started at the impact point in a thick composite sample. The off-axis case was characterised by a mixture of damage modes. An extension of the damage zone (the region with high micro-stresses) into the zone aligned with the fibre direction was observed and the extension damage zone was noticeably larger than that for the case of a target that has the material symmetry axis aligned with the loading direction.

Concluding, it should be noted that the major drawback in further development of constitutive models for damage variables is a lack of experimental data in order to determine numerous parameters of the equations. An experimental methodology is also absent, which would allow researchers to link the damage parameters with the experimental data that are available or that have to be obtained.

6. Damage response to the ballistic threat

6.1 Failure mechanisms

The material response of a composite target to ballistic impact is characterised by a shorter time of applied load (the projectile-target interaction time), when compared with the LVI load time. Post-mortem examinations of composite targets subject to ballistic impact, focus on the study of the extent of the damage concentration (localisation of the damage) against the impact velocity. There is a connection between the material mechanical properties and the ballistic performance (the damage resistance to ballistic impact). Other mechanical properties (in particular, the stress-strain response) have been studied in a number of works (see review in Section 3). Interdependencies between the ballistic performance and the mechanical properties of several Titanium alloys were studied in paper [Meyer, 1997]. 20-mm FSPs have been used in the ballistic tests of this study. It was found that the appropriate interdependency parameters are failure strain during compressive tests, compressive dynamic strength and a sensitivity parameter to adiabatic shear under dynamic biaxial (compression-shear) conditions.

There is a large number of ballistic performance studies for targets made of composite materials. For example, paper [Abrate, 1994] provides a review that focuses specifically on composite targets. The review quite thoroughly outlined the literature related to damage mechanisms in composites during impact and the residual properties of composites after impact. However, this review provided just a few references to the evaluation of the ballistic limit and residual velocities. Moreover, it did not consider oblique impact issues nor touch upon specific topics related to the semi-empirical dependencies for composite targets. The review shows that there is an increasing concern about composite material

response to low-velocity impact. Special attention was paid in the review to the effect of fabrication-induced thermal micro-stresses on impact response.

A study on the localisation of damage and damage concentration with impact velocity has been conducted in paper [Ruiz, 1998]. Target panels were made from unidirectionally reinforced C/epoxy (T300/914) composite plates consisting of 21 alternating 0/90 layers. In this paper, the impact tests simulated bird impact on aircraft blades and panels. Compact 10g-weight impactors (the impactors' density range was from 0.9 to 1.1 g/cm^3) launched with a velocity up to 600 m/s and at an attack angle of 40° were used in the tests with the projectiles accelerated by a gas gun. The target dimensions were approximately 20 x 10 cm. The total destruction of a panel was observed with an impact velocity of 280 m/s; extensive cracking and delamination at an impact velocity of 240 m/s; and small damage at an impact velocity of 200 m/s. The authors observed a relatively large area of plastic deformation at subcritical velocities of impact. An increase in the impact velocity resulted in stronger localisation of the damage area around the impact point.

The failure modes of a composite target are also frequently analysed with the help of post-mortem examinations. Usually, the delamination area is considered to be a characteristic of damage and so the delamination area might be associated with the ballistic resistance. However, methods of assessment of delamination due to impact damage vary significantly from one publication to another. Evaluation methods may involve visual inspection, evaluation of the delamination by transmitted light, C-scanning, X-ray photography and others (see subsection 3.5 for a list of relevant methods). Also, there are some attempts to relate damage properties and the ballistic resistance of composite targets to some geometrical characteristics of the damage zones. For example, in paper [Nunes, 2004], flatbed scanner images of the delamination were categorised according to the shape factor of the delamination zones, allowing the damage resistance to be associated with the shape factors of the image. However, internal delamination cannot be assessed with such an approach and analysis of damage dynamics, including the progression of damage and type/mode of damage, cannot be conducted in this way.

Paper [Fujii, 2002] reports on a general trend for CFRP samples with different fibre strength, which were analysed with post-mortem examination. This study has shown that impact delamination for laminates with stronger fibres and larger failure strain (the high-strength-fibre CFRPs) is larger and deeper. This paper [Fujii, 2002] also showed that within the range of high velocities (from 500 up to 1230 m/s), fracture occurs in a fluid manner for thin 2 mm-samples. This 'fluid-like' fracture is characterised by stress levels which are much higher than the Hugoniot elastic limit, so strength effects could be neglected when considering the penetration process. For thicker 6 mm-samples, the front layers of the target were damaged in a fluid-like manner as before, but the rear layer was damaged in an extrusive manner with a plugging mechanism and delamination. The delamination width increased with impact energy for thick laminates but remained constant for thin laminates. This trend of delamination size increase is associated with a change of the failure mechanism. For CFRP with low-strength fibres (when compared with high-strength-fibre CFRPs), the fracture area increased for the impact side plies and decreased

for the rear side plies. This occurred because the damage mechanism for the thick low-strength-fibre CFRP samples is plugging failure (in comparison, the damage mechanism for the high-strength-fibre CFRPs is delamination). The failure mechanism for thin targets in this velocity range is fluid-like and the fracture is smaller. For thick targets the failure mechanism for laminates at the rear side changes from plugging to fluid-like with an increase of the residual velocity. This also happens for laminates with small failure strain (low-strength-fibre CFRPs). For laminates with high strength fibres and large failure strain (high-strength-fibre CFRPs) the mechanism changes from delamination to the fluid-like mechanism as the velocity increases.

Plain weave glass/epoxy and twill weave carbon/epoxy composites subject to ballistic impact have been numerically analysed in paper [Naik, 2004]. This analysis considered two types of yarns: primary yarns (those that are the direct continuation of the fibres under the projectile hit area) and secondary yarns (all the rest). The analysis has shown that the ballistic limit velocity is higher for the glass/epoxy composite. The main absorbing mechanism for this composite is the tensile failure of the primary yarns and deformation of secondary yarns. The tensile failure mechanism is dominant for glass/epoxy composite because the glass fibres have high shear strength. Deformation of the secondary yarns along with shear plugging is the major absorbing mechanism for carbon/epoxy composite. Fibre orientation effects have been observed in paper [Bartus, 2005]. When testing randomly oriented fibre composites under ballistic impact, cracks propagated into the areas where fibres are highly coordinated (along the fibres) and are arrested in the areas where the fibres are grouped in chaotic orientations.

The paper [Gellert, 2000] has analysed the ballistic impact of conical and flat projectiles against glass-fibre plastics. The test results reveal that the dependence of impact energy at the ballistic limit velocity (this critical energy can be reduced to the perforation energy) is a bilinear function of the target thickness. The fracture analysis demonstrated that indentation and dishing are two main deformation mechanisms, which are responsible for perforation. The indentation and dishing energies are linear functions of the target thickness, so the perforation energy, which is just a sum of those, is a bi-linear function. The dishing effect is observed mainly at small thicknesses of the targets and a combination of indentation that is associated with the fibre breakage and dishing is observed for thick targets. Paper [Silvestrov, 1995] observed that the damage area in glass-fibre laminates under hypervelocity impact was of approximately the same hourglass shape as the damage observed in the paper [Gellert, 2000] under ballistic impact.

Damage mechanisms of a composite laminate (Kevlar fabric) have been analysed numerically in paper [Silva, 2005] when the composite targets are subject to ballistic impact. The damage character of the laminate plies in the through-thickness direction (from the frontal side down to the distal side of the target) changed from a matrix cracking mechanism at the frontal side to a pure delamination mechanism at the rear side of the target, if the impact velocity was below the ballistic limit velocity. Higher localisation of damage was observed at higher impact velocities, in which case the primary damage mechanism was fibre failure at the projectile contact point. In contrast to the results of

[Silva, 2005], for a flexible fabric such as Spectra Shield (polyethylene filaments in epoxy resin), the impact results that were described in paper [Tan, 2005] demonstrated damage over a larger target area and with more energy absorbed. The damage and the energy both increased with increasing impact velocity regardless of the projectile shape.

A study of the damage mechanism of unidirectional and quasi-isotropic carbon-fibre composites, which were impacted by spherical steel projectiles (the projectile diameter was 12.7 mm) at an impact velocity of 470-480 m/s, has been undertaken in paper [Hammond, 2004], using in-situ high-speed photography. The fine-grid technique (see [Rae, 1999]) was used during photographic observations of the targets' rear side and the composite target's thicknesses varied from 2 to 3 mm. The observations revealed that initially (at the moment of the projectile's entrance into the target), the target was damaged just in the vicinity of the projectile diameter. Major damage spread occurred after the projectile exited the target. This damage was associated with target flexure after the penetration. For quasi-isotropic composite targets, cracking occurred in the outer ply both in the fibre direction and orthogonally to the fibre direction, which resulted in the ply's delamination. From the observations, the remaining material out of the deformation zone (the 2-3 projectile-diameter zone) did not appear to be significantly deformed. For unidirectional composite targets, cracking occurred in the fibre direction and quickly spread along the whole sample with deformation across the fibres (orthogonally to the fibre direction).

Paper [Cristescu, 1975] analysed the failure mechanisms of glass/epoxy 0/90 composite targets perforation by 1 cm-diameter cylindrical steel projectiles launched by a gas gun. The composite structure was composed of laminas with alternating orientations (0 to 90 degrees) to each other and several layers of unidirectional fibres in each lamina. Delamination was never observed between the layers within a lamina; instead, it occurred between the laminas. This study suggested that the typical failure mechanism was indentation of the projectile in the first lamina, which caused fibre stretching while cutting-out the lamina. The stretching resulted in strain-induced delamination that progressed over the fibre stretch area. The process developed lamina-by-lamina. The more layers within a lamina, the stronger its resistance to plugging and the larger the corresponding delamination area. Increasing the number of layers in each lamina of the targets (from 3 to 5) resulted in a greater (about 5% increase) penetration resistance where the measure of the resistance was the absorbed energy evaluated as $2/M \cdot (V_i^2 - V_r^2)$. The tests, demonstrating the highest resistance, also exhibited the largest delamination areas. The paper [Cristescu, 1975] also listed other damage mechanisms, such as fibre breakage by tension (specifically for tipped projectiles) and fracture by bending of fibres at the distal side of the target (acceleration of the rear side after shock wave reflection from the free surface). Evidence of large tensile stretching of fibres close to the distal side was available. One more damage mechanism, contributing to the delamination, was damage due to the reflection of waves from the lamina interfaces and due to the shear induced by the inter-lamina shear waves. For more ductile composites, fibre pull-out and stretching were suggested as energy absorbing mechanisms at penetration. Paper [Ross, 1973] studied the influence of the distribution of differently oriented layers (the 0 and 90 degree layers) in the glass/epoxy 0/90 laminates at the ballistic limit velocity. An indication of V50-

reduction was observed for an equal distribution of the 0 and 90 degree layers with the least V50-reduction observed for a unidirectional composite structure.

Paper [Sierakowski, 1981] analysed in-plane failure mechanisms of glass/epoxy ($0_5/90_5/0_5$) composite systems due to impact by steel projectiles. The 9.5 mm-diameter projectiles used were blunt-nosed and hemi-spherically nosed. Some influence of nose shape on failure modes was observed. For the blunt nosed projectiles a generator strip (a piece of lamina delaminated from the target along the fibre direction) of width 2*D* (*D* is projectile's diameter) ran along the fibres at the rear (distal) side of the target. Hemi-spherical nose impactors generated localised delamination, at the same time generating a single crack. Transverse cracks parallel to fibres and propagating in the through-thickness direction were noticed. The cracks were associated with micro-stresses that appeared during material manufacture. These cracks were observed at the front and rear of the target and the distance between the cracks decreased with an increase of the impact energy. Embedded strain gauges in the midplane of the target and surface strain gauges were used in order to study wave transmission effects. The paper [Sierakowski, 1981] concluded that the predominant waves which transmit strain, are the flexural waves and therefore, delamination is mostly wave-induced by flexural waves. Observations made with high-speed photography with conductive silver painting at the rear surface of target revealed that the delamination propagates at a velocity of 300-500 m/s and the generator strip at an initial velocity of 600-700 m/s.

With the development of novel weapons, new threats to composite targets arise and new damage mechanisms to composites can be involved when responding to the new threats. For example, matrix combustion with a high-temperature threat or matrix loss is a new damage mechanism due to a Slew Beam Laser threat (see [Caravasos, 1998]). The appearance of new threats will probably challenge researchers to evaluate structure vulnerability in unusual conditions such as those associated with the effects of direct-energy or thermobaric weapons.

6.2 Ballistic limit velocity (V50), absorbed energy, and failure

As mentioned in Section 1, ballistic impact results in two damage threats: i) damage to a target (e.g., helicopter skin); and ii) damage to behind-target objects due to after-perforation debris that can carry high kinetic energy. This Section focuses on assessment of behind-target damage, so the composite skin is not the object of study. Being a protective screen, the skin may absorb impact energy and affects the residual penetration capacity of a projectile.

Ballistic tests are conducted on ballistic ranges or in gas gun facilities. There are a number of standards classifying such facilities. An example of a ballistic range description and layout can be found in a well-know military standard [Military Standard, 1966]. Examples of ballistic testing methodology were outlined in review [Mascianica, 1980]. Earlier tests included arena tests of high explosive (HE) shells. Information about the distribution of weight and size of fragments was recovered from the post-mortem analysis of witness

plates or packs. A more recent (just after the World War II) US specification for High-Explosive Incendiary (HEI) shells contains details for a ballistic range facility. For 20 mm calibre HEI shells, a 3.2 mm thickness steel triggering plate is placed 1 m ahead of an armour panel. Shells are fired into the target with a velocity of 838 m/s. The triggering plate initiates detonation of the 20 mm HEI shells and 'forward spray fragments' impact the armour target. The test is called the 'forward spray test'.

In the majority of tests, the ballistic limit (BL) velocity is a criterion of the target protective properties. However, this criterion is not completely defined. For example, the US defence department uses at least three BL criteria: the Army Ballistic Limit (ABL), Navy Ballistic Limit (NBL), and Protection Ballistic Limit (PBL). They differ from each other in the extent of target penetration by a projectile and in the extent of damage to the behind-target witness plate. For the ABL criterion, the projectile's nose should be visible from the back of the target. For the NBL criterion, the projectile's full passage through the target is the key observation (from the viewpoint of the ship's survivability, when the ship's wall is subject to the ballistic impact). The PBL criterion requires that a sheet of aluminium alloy (0.05 to 0.5 mm thickness located 15.24 cm behind the target) should be pierced at the ballistic limit velocity.

However, the most popular BL definition is the Ballistic Limit Velocity (V50). This definition is based on a 50% probability of penetration of armour. For determining the BL, the authors of the review in [Mascianica, 1980] suggest a testing methodology based on an incremental change of propellant weight on successive rounds in order to achive an impact velocity increment of the order of 30 to 60 m/s. It is suggested that the propellant charge is always 'decreased by the same amount after obtaining a complete penetration and increased the same amount after a partial penetration'. After the penetration event has occurred, the propellant weight can be reduced by smaller amounts. The introduced 'up-and-down' scheme should be always used and the velocity increment should be no more than 10 m/s. Other widely accepted definitions of the ballistic limit, the BL velocity (V50), the obliquity angle, and other terms related to ballistic tests are available in a military standard [Military Standard, 1997].

A multiple cube test was developed for launching a number of cubes of a pre-given mass and size carried by one sabot (see [Mascianica, 1980]). The V50 velocity was determined as the velocity at which half of the cubes striking the target will defeat it. This test set-up was later replaced by a single cube test with a steel cube of a given size and mass mounted in a plastic sabot and fired from a rifled gun. The sabot is caught at the muzzle and the cube may strike target either by side, by edge or by corner. This uncertainty increases the scatter in the ballistic data. An alternative test set-up involves single or multiple spheres that are launched by a smooth bore or rifled gun (the spheres are carried in a plastic cap or a sabot, which is destroyed).

Typically, methods for assessment of penetration efficiency involve the following criteria: (1) an event of penetration or non-penetration of a target under specified conditions; (2) the depth of penetration into a thick witness pack (the witness pack is required to stop the

projectile) made either from a soft homogeneous material or from a number of layers of a standard material (e.g., wood); (3) a value of V50, which is the projectile velocity required in order to penetrate the target with 50% probability; (4) a magnitude of the projectile's residual velocity after the projectile has passed through the target; and (5) the minimum angle of obliquity at which the projectile will be defeated by the target at a constant projectile velocity. More complex tests involve impact by projectiles of various sorts (fragment simulating projectiles – FSPs) including parallelepipeds, yaw dart missiles, etc. The idea of using FPSs is to simulate the fragments of actual HE shells and fragmentation warheads with a range of shape factors.

V50 and the residual velocity V_r after impact are of primary interest in ballistic studies. Therefore, a number of methods and theories have been developed in order to link V50, V_r and the impact velocity V_i. Paper [Kasano, 1997] verifies several the widely known residual velocity formulas. The formulas are usually based on the momentum conservation law:

$$M_0 V_i = M_0 V_r + m_0 V_r + I \quad ,$$

and the energy conservation law:

$$\tfrac{1}{2} M_0 V_i^2 = \tfrac{1}{2} M_0 V_r^2 + \tfrac{1}{2} m_0 V_r^2 + E_p \quad .$$

Here I is the momentum transmitted to the target and E_p is the energy lost during perforation. Based on momentum or energy conservation laws, two analytical models are derived, which result in the following connection between the impact, residual, and ballistic limit velocities:

$$\begin{aligned} &\text{Model } A\text{: } V_b^2 = V_i^2 - a\, V_r^2 \\ &\text{Model } B\text{: } V_b^2 = V_i^2 - a^2\, V_r^2 \quad , \end{aligned} \tag{3}$$

where $a=M/(M+m)$, M is mass of the projectile, m is mass of the plug pushed out from the target by the projectile, and V_b=V50. Verification of the formulas for aluminium and CFRP plates conducted in this study [Kasano, 1997] demonstrated that model A best described results for the CFRP plates, whereas the model B best described the penetration results for aluminium plates. It appears that the authors ignored the fact that the momentum and energy contributions for CFRP plates are much less than for aluminium plates (mainly due to the brittle character of fracture in CFRP, when compared with the ductile fracture in aluminium – the plug is well formed in the case of aluminium targets). Therefore, for CFRP plates the parameter a is likely to be close to 1. Neglecting this mechanism increases the a-influence for model B. Thus it may be that the variability of the results is caused by differences in the fracture mechanisms. From the tests [Kasano, 1997], the ballistic limit velocity is related to the target thickness t as a linear dependence ($V_b=b_0t$). An analytical model based on the same assumptions was suggested for a multi-layer target but this model was not verified experimentally. For all cases, normal impact only was considered.

An analysis of the different models listed by equation (3) for experimental ballistic test data [Resnyansky, 2004c] has been conducted in paper [Resnyansky, 2004d]. The value of the parameter a = 1 was substantiated for thin carbon/epoxy quasi-isotropic targets at both normal and oblique impact (the obliquity angles were 30° and 60°). The impact velocity varied within the range of 400-900 m/s (using standard military 5.56, 7.62, and 12.7 mm, rounds). However, for thicker composite targets (more than 4-6 mm in thickness), the obliquity angle and the target thickness are factors that should be taken into consideration. Paper [Walker, 2001] described a simple theory of the ballistic performance of a Kevlar fabric. Experimental deformation of composite targets was observed and parameters of the deformation were used as input parameters for evaluation of ballistic performance. Using a linear approximation, the ballistic limit velocity was assessed via the stretching deformation in the composite target as

$$V_b = K\,(1+ \beta\, X)\, c\, \varepsilon_f\,,$$

where K and β are constants, $X=AD/M_p$ is the ratio of the areal density AD to the mass of projectile M_p, c is the 'wave' speed in fibres, and ε_f is a failure strain (the failure strain is associated with fabric stretching strain at failure). This model has been verified with ballistic tests (7.62 mm-AP-projectiles against ceramic/metal target backed by the fabric, which is called a spall liner) conducted in paper [Orphal, 2002]; the fabric deformation was traced with the high-speed photography and the modelling results were fitted to the test data.

Two analytical models for the residual velocities following high-velocity impact against composite and metallic targets have been reported in the paper [Kasano, 1997]. For verification of the models, a series of ballistic tests were conducted for composite (orthotropic and quasi-isotropic CFRP) and A5052 aluminium targets. The projectiles used were 5 mm-diameter 0.51 g-weight steel balls with a maximum impact velocity of 330 m/s. Ballistic limit (V50) and residual velocities for the targets up to 5 mm in thickness were found. The models were extended to the multi-layer case with up to 4 layers for the aluminium targets. Paper [Landa, 1988] reported on a semi-empirical model in order to calculate ballistic curves for Kevlar/Epoxy composite targets. The response of an individual lamina and the corresponding reduced tensile force (that is in agreement with the absorbed energy) were considered based on a beam theory, using the mass and kinematic characteristics of the projectile. This consideration resulted in a semi-discrete one-dimensional model which was used for a description of V50 versus the areal density of the target.

Understanding how the damage mechanism of a target material is associated with the ballistic limit velocity V50 is important for the purpose of evaluation of damage tolerance. Paper [Lee, 1993] considered the response of graphite/epoxy laminates subject to impact by 14.5 mm blunt-ended projectiles launched by a gas gun. Measurement of the residual velocity of projectiles was performed by a system that contained glass plates with conductive print on their surfaces. These produced a capacity-discharge induced signal to

an oscilloscope on breakage of the plates. The maximum span (the diameter of the open area) of the composite specimens was 9 cm and the total in-plane linear dimension was 15 cm. Delamination was observed over the whole area of the specimens. It was concluded that the major damage modes of the target material were delamination and plugging. The ballistic limit velocity was determined in the paper [Lee, 1993] according to the following formula

$$V50^2 = V_i^2 - a \cdot V_r^2 \ . \qquad (4)$$

From the static punch data obtained in the same study it was concluded that the damage starts with matrix cracking followed by delamination during continuing loading. Next (the second stage of penetration), softening due to stress relaxation in the damaged material plays a role (this stage corresponds to the load release after the first maximum of the force-displacement response). After this load drop, the load increases again to a second maximum when plugging suddenly occurs followed by pushing out of the plug. A relatively slow release occurs after that, accompanied by friction between the projectile-plug assembly and the edge of target opening. A relatively small stable force response was observed during this friction process between the projectile and target in the third stage of the penetration. The ballistic resistance curves ((V_r , V_i) dependencies) were described quite well using the formula (4). The recommendation of the study was to use formula (4) when V_i is as close to V50 as possible, because there is a trend of increasing V50 with an increase of V_i.

In paper [Takahashi, 1997], the residual velocity was reported for penetration tests of fabrics intended for a bullet-proof cloth. The projectiles were steel 9.5 mm-calibre bullets of 3.55 g-mass, launched by a gas gun. Polyethylene fibres were impregnated into resin and different textile structures were tested with velocities of impact up to 200 m/s. Samples were cylindrical-shape specimens clamped within two steel rings. The open testing area had a diameter of 75 mm. It was shown that the perforation energy increased with an increase of the impact velocity up to a critical velocity (an analogue of V50), followed by a perforation energy decrease after the impact velocity exceeds the critical velocity value. The perforation energy increased linearly with the sample's areal weight. Two penetration mechanisms were noted to be important during the perforation of the material: i) fibre pull-out; and ii) cutting of yarns.

Paper [Nandlall, 1999] reported on the ballistic performance of a polymeric composite. A critical penetration velocity $V_{c,}$ better known as V50, was fitted to the impact V_i and residual V_r velocities, using the Lambert-Jones ballistic equation in the following form:

$$V_r^p = a_0(V_i^p - V_c^p) \ . \qquad (5)$$

Papers [Anderson Jr., 1996; Anderson Jr., 1999b] reported on the results of high-velocity impact by long rod projectiles of different hardness. It was observed that the depth of penetration of semi-infinite targets is a strong function of the projectile hardness. The influence of hardness on ballistic performance was considered in the paper [Anderson Jr.,

1999b]. Projectiles were flat-nosed rods and the targets were two different-hardness steels of 2 cm in thickness. The Lambert-Jones formula (5) was reduced to the following:

$$V_r/V_b = a[(V_i/V_b)^p - 1]^{1/p} ,$$

V_b is the same as V_c in formula (5). All of the ballistic penetration data in this paper were fitted to one curve in (V_r/V_b, V_i/V_b) coordinates. The relationship was approximated using least-square analysis by the following:

$$V_r/V_b = (a_1 x^2 + a_2 x + a_3 x^{0.5})/(x + 1) , \qquad x = V_i/V_b - 1 , \qquad x \leq 2.5$$

The residual length of the projectile was also studied in this work. It was found that length erosion is significant for targets made from steel which has a hardness higher than the hardness of the projectile material.

Other ballistic limit criteria can also be used. For example, paper [Gupta, 1966] described ballistic impact tests, using Winchester 5.6-mm projectiles and 30-06 rifle 7.62-mm projectiles. Impact against glass-fibre-reinforced plastic (GFRP) targets was considered. Energy loss and the ballistic limit thickness (the target thickness at which the projectile has just been stopped) were found to have a linear dependence on the impact energy.

Paper [Goldsmith, 1995] describes the static and ballistic testing of carbon/epoxy laminates against indentation by 60° conically nosed 12.7 mm tups and impact by similar projectiles. The target thicknesses T varied up to 6 mm. The test results demonstrated that ballistic perforation energy is higher than static perforation energy. The velocity V50 was found to be linearly dependent on target thickness for thick targets. At small T, the (V50, T) dependence was non-linear, possibly, bi-linear.

A large area of study of composite target response is associated with analysis of failure mechanisms and with linkage of the mechanisms with energy absorption under ballistic impact. This topic is closely related to V50 studies, because the absorbed energy E_a is frequently calculated as the difference between the initial and the residual kinetic energies of a projectile. These connections give ballistic resistance curves which are dependencies of the residual velocity versus the impact velocity.

Traditionally, evaluation of E_a was first conducted for ductile targets. For example, paper [Gupta, 2001] considered the ballistic impact of ogive-nosed projectiles (the diameters of the projectiles were within the 10-15 mm calibre range) against thin aluminium targets (the target thicknesses were 0.5-2 mm). The open target area subject to impact was nearly 20 cm in diameter. The projectiles were launched with a gas gun with impact velocities of 10-100 m/s. The ballistic resistance curves were compared with semi-empirical formulas. The penetration energy is the same as the absorbed energy:

$$E_p = ½ V_b^2 = E_a ,$$

if the mass of the plug pushed out from the target is negligible. In this paper [Gupta, 2001], the following formula for the penetration energy was suggested

$$E_p = ½\, k \cdot Y\, d \cdot h^{2n} ,$$

where k is a fitting constant, Y is the target's yield limit, d is the diameter of the projectile, and h is the target thickness. These results were compared with calculations, using other semi-empirical penetration-energy formulas of the general form $E_p = s_u\, d^n h^m$, where s_u is the tensile strength of the target, and n and m are empirical constants.

For composite targets, evaluation of E_a is more complex because the structure of composite material should be considered in the analysis. Paper [Bless, 1989] described a series of ballistic tests, using FSPs (the projectile diameters varied from 5.6 up to 20 mm) against fibreglass/epoxy laminates. The test results showed that V50-data for composite targets with different volume concentrations of the fibres could fit to one straight line linking V50 with $\rho T/D$ (the variable parameter is the areal density ρT, where ρ is density of the target material and T its thickness over the projectile diameter D). Analytical evaluation of the penetration energy E_p, which is proportional to ½ $V50^2$, gave the following formula

$$E_p = ½\, s\, \rho\, D^3\, V50^2 = ½\, \pi\, DT^2\, Y_T ,$$

here s is the shape factor of the FSP for calculation of the projectile's volume (s=0.86 for the FSP) and Y_T is the transverse strength of the composite laminate. This evaluation followed from analysis of the mechanism of shear failure, where shear occurs at the edge of the projectile's periphery. This analysis indicated proportionality of the ballistic velocity V50 versus T/D.

Paper [Takahashi, 1997] reported on ballistic tests with polyethylene fibre textile targets. The ballistic limit velocity was used for assessment of the absorbed perforation energy. This energy E_c was evaluated in the usual way:

$$E_c = ½\, m V_b^2 \; .$$

The perforation energy was used for assessment of the specific energy E_s that is related to the areal weight density W (which is the weight of the target material per 1 m^2):

$$E_s = E_c/W \; .$$

The absorbed energy E_c can also be calculated from the difference between the projectile's kinetic energies before and after perforation:

$$E_c = E_i - E_r = ½\, m\, (\, V_i^2 - V_r^2) \; .$$

The study in [Takahashi, 1997] claimed that the critical energy E_c has a maximum at the ballistic limit velocity, and the perforation energy depends linearly on the areal weight

density of a fabric target. A closer examination shows significant scatter in the dependence of E_c on V_i (up to 50%), so the claim about the maximum of E_c appears to be unreliable. E_s was assessed for several types of fabric and the assessment revealed significant differences in the specific energies for different types of fabric. Recalculation from the ballistic limit velocities and the stated areal densities gave values of the specific perforation energy of 73-75 $J \cdot m^2/kg$ with maximum scatter of approximately 7%.

Paper [Van Gorp, 1993] reported on the ballistic response of fabrics with High Performance PolyEthylene (HPPE) fibres. The V50 velocity was measured for a range of FSPs that have weight W in the range from 0.237 to 13.4 g. Energy absorption was linked with V50 as usual. Test data were analysed in this study and the following semi-empirical formula was deduced, which linked V50 with the areal density AD and weight W:

$$V50 = C \cdot AD^{1/2} \cdot W^{-1/6} \ .$$

A similar formula for steel targets was also stated in the paper:

$$V50 = C \cdot AD^{3/4} \cdot W^{-1/3} \ .$$

Paper [Sun, 1996] described experimental data and suggested a theory for projectile penetration into thick graphite/epoxy laminates (the target thickness was from 4 to 8 mm). The projectiles were flat-ended and 14.6 mm in diameter. The target dimension (the open circular area subject to the impact) was from 5 to 8 cm in diameter. Static tests recording the load response of the targets, which were also conducted in this work, showed a load increase up to the start of delamination, followed by temporary matrix softening. A second load increase occurred up to the moment of fibre breakage. After the second load increase a plug formed, which resulted in a sharp force-drop followed by a gradual decrease of the resistance load until the plug left the target. This gradual load decrease was characterised by a relatively long residual load due to projectile-target friction. Using the load-displacement curve, the static penetration energy E_{sp} can be assessed from the data (by integration). Thus, the first approximation of the residual velocity can be obtained from the energy balance relating the perforation energy to the difference of the projectile's kinetic energies before and after the penetration:

$$V_r = (V_i^2 - 2E_{sp}/M)^{1/2} \ ,$$

here M is the projectile's mass. The dynamic (ballistic) tests recorded the impact and residual velocities of the projectile and from these data, the dynamic penetration energy E_{dp} can be assessed as

$$E_{dp} = \tfrac{1}{2} M \left(V_i^2 - V_r^2\right) \ .$$

Assessments from the static and dynamic data demonstrated that $E_{dp} > E_{sp}$. The dynamic tests showed no difference in penetration energies for tests against targets with different

sample spans. A simplified penetration model described in this paper [Sun, 1996] was based on the anisotropy plate theory. After the first load peak, the shear modulii were modified in order to describe softening, keeping the in-plane modulii constant (assuming no fibre breakage). The shear modulii were degraded uniformly from the target's centre over the span and progressively versus the time of indentation in order to describe the experimental load-deflection slope. It was assumed that a plug formed after reaching the second load peak. In dynamic finite-element modelling, the target's critical deflection was used as a criterion for damage onset.

The study reported in [Hammond, 2004] of composite response to ballistic impact against quasi-isotropic ($[0,\pm45,90]_{2S}$ and $[0,\pm60]_{3S}$) and unidirectional CFRPs (this study was mentioned in the present subsection) demonstrated that energy absorption is larger when more lamina plies with alternating directions are involved. Thus, minimal energy absorption was reported for a unidirectional composite even if the crack area was observed along the whole length of the sample. A larger absorbing capacity was reported for quasi-isotropic structures (the energy absorption was evaluated as the difference of the kinetic energies of the projectile before and after impact). For a $[0,\pm45,90]_{2S}$ composite, the post-impact area of damage was spread approximately over an area of three projectile diameters and for a $[0,\pm60]_{3S}$ composite, approximately over an area of two projectile diameters. In these cases, the observed (energy absorption –composite structure) correlation was confirmed because energy absorption was larger for the $[0,\pm45,90]_{2S}$ composite than for the $[0,\pm60]_{3S}$ composite targets.

Testing of foam-core panels (40 mm in thickness) sandwiched between glass/epoxy 4 mm-laminate face-sheets (a quasi-isotropic lay-up) is reported in paper [Skvortsov, 2003] at impact velocities of nearly 80 m/s, exceeding the ballistic limit velocity (approximately 40 m/s). The sandwich panels were either simply supported or backed by an anvil, in which case the anvil had an opening for the passage of the projectile. The absorbed energy was calculated as the difference between the impact and residual kinetic energies of the projectile (the residual velocity was estimated by the method of the ballistic pendulum). The objective of the paper was to evaluate the damage and elastic energies of penetration as contributions to the absorption energy of the panels. Delamination in the face-sheet laminate was observed in directions perpendicular to the principal fibre direction. The size of the delamination area was used for assessment of the damage energy of the simply supported panels. It was assumed that the backed samples absorbed impact energy without an elastic component (i.e., the total absorbed energy was equal to the damage energy). From analytical assessments of the damage energy, it was found that the elastic energy was usually more than 50% of the total absorbed energy. It was also found that the damage energy for the backed panel was 20% higher than the damage energy for the simply supported panel. It should be noted that variations in the assessment of damage energy could exceed 20%. Nevertheless, the fact that the damage energy is a minor part of the absorbed energy for the unsupported sandwich panels is quite remarkable. However, the study pointed out that at higher velocities, the energy damage part is dominant.

6.3 Factors affecting V50, hybrid targets and appliqué armour

An important factor affecting V50 is the target issues that may include the complexity of a target (e.g., spaced components and hybrid targets), manufacturing methods (e.g., ply sequencing), constituent treatment, susceptibility of constituents to the environment, etc. The question of how ballistic performance is influenced by target decomposition into several layers may be seen in LVI response studies (e.g., see a review in subsection 5.5). In those studies an attempt was made to increase absorption energy by the introduction of free surfaces in a complex target by air gaps or intermediate layers. Paper [Woodward, 1998] analysed the fracture mechanisms of aluminium targets under ballistic impact. A variety of fracture mechanisms was initiated at different target thicknesses starting from plugging, through discing (this mechanism exhibits bending cracks at the target's distal surface), and ending with a dishing mechanism, where a tensile mode of fracture dominates. Layered combinations of aluminium plates (keeping the total thickness constant) were studied under ballistic impact by flat-nosed and cone-nosed projectiles. Analysis of the involvement of the various mechanisms for different target and projectile configurations was performed and the effect of the configurations on the ballistic limit velocity was determined. Another study [Woodward, 1991b] revealed a higher ballistic limit (that means a higher absorbed energy) for an unbonded stack of steel layers when compared to a solid single steel target of the same areal density.

Paper [Radin, 1988] considered the effect of high-velocity impact by cone-nosed and blunt projectiles against combinations of aluminium and Lexan plates. The velocity of the projectiles was near the ballistic limit velocity and higher. A part of this study extrapolated the ballistic penetration data (the penetration depth in a witness plate behind the target versus the impact velocity) to zero depth of penetration and this provided a first approximation of the ballistic limit velocity V50. This study [Radin, 1988] showed that: i) V50 is lower for two layers than for a solid target of the combined two-layer thickness; ii) V50 is lower for separated layers than for the same layers in contact and; iii) V50 is lower for several layers of different materials than for one monolithic target of the same combined thickness made of the either of the materials. It is interesting that result (i) contradicts the results reported in [Woodward, 1991b] and the possible influence of the number of layers and the ratio of the projectile dimensions to the target thickness has yet to be analysed.

Paper [Radin, 1988] did not consider the effects of synergism, which are common in ceramic/ductile material hybrid targets (so called appliqué armour). It is interesting, however, that the same conclusions (i-ii) above, could apply to ceramic/aluminium hybrid targets. For instance, paper [Partom, 2001] reports that a doubled spaced target (two ceramic/ aluminium hybrid targets made of a 4.6 mm-layer of ceramic backed by a 3.1 mm-layer of aluminium separated by an 82 mm air gap) has worse ballistic protection performance than a single assembly with approximately the same areal density (a ceramic/aluminium hybrid target made of 9.2 mm-layer of ceramic backed by a 6.6 mm-layer of aluminium). It should be noted that the aluminium layer was a little thicker than the combined thickness of aluminium in the double target. However, the depth of

penetration (DOP) was dramatically different for the two cases (nearly 5 mm against 2 mm).

Structural elements (layers) of hybrid targets, even if they have a low impact resistance, may introduce synergism when combined with a main protective layer. For example, impact against a brittle target made of Pyrex glass can be effectively damped, which is manifested by an increase of the absorbed energy and by a reduction of a projectile's residual velocity, if the target is encased by thin composite layers (see [Kim, 2004b]). This simple confinement (encasing), which has negligible impact resistance on its own, prevents the development of extensive cracks, which is typical for brittle materials. It should be noted that different hybrid target structures appear frequently in military applications under different terms such as appliqué armour, spall liner, etc. However, this basic idea exploits a principle of synergism in hybrid targets. Semi-empirical relationships for the calculation of the ballistic limit velocity using mechanical properties of the constituents of appliqué armour are very popular because they are related to the redistribution of the impact energy over a wide area of the main protective layer, using the sacrificial brittle layer. Application of such formulas, previously used mainly for conventional metallic materials, to the case of composite armour subject to ballistic impact is reported in paper [Ben-Dor, 2005]. Optimal parameters (thicknesses) of a two-component armour system have been reported in this paper. Another analytical model for calculation of V50 is noted in paper [Prior, 1986] for two-component armour. The frontal component (layer) of the armour was a ceramic plate (Al_2O_3) and the backing plate was made of GFRP. The modelling results were verified for the case of ballistic impact by 7.62 mm-calibre steel balls of 9.33 g mass. V50 for this case was found to be 800-900 m/s for armour with a 9.5 mm thickness layer of GFRP and for a ceramic facing plate of 4.5-5.5 mm thickness.

Ceramic plates in front of a composite protective layer could be used in order to deform a projectile. Instead of ceramic plates, in paper [Ko, 1997] a layer filled with ceramic spheres was used as the destructive layer in front of a Spectra polymer composite layer. The purpose of the frontal layer was to redistribute the impact energy over a wider area at the point of impact. The layer consisted of ceramic spheres of various sizes embedded into an epoxy matrix. The backing layer was made of Spectra Shield composite, which had various thicknesses for the series of tests conducted in [Ko, 1997]. The targets were 30 x 30 cm panels. One to four shots were fired against every sample followed by an inspection after each shot. The panels were positioned normal to the line of fire. Projectiles were 7.62 mm-calibre bullets with a lead core encased in a brass jacket and the weight of the projectiles varied from 7 to 9 g. The V50 velocity was defined as an average of the highest partial penetration velocity and the lowest complete penetration velocity. An aluminium 0.05 mm thick witness plate was mounted at a 15 cm stand-off behind the target sample. V50 was determined for a range of sample thicknesses (from 2 to 3 cm), varying structures of the backing plate, and a range of sphere distributions in the front layer. For 2-3 cm-thickness targets, the V50 values varied in the range of 1200 to 1500 m/s.

Paper [Lexow, 1999] analysed the ballistic performance of steel/composite targets (spall liners). The impact velocity was approximately 830 m/s in all cases. Projectile residual velocity was evaluated for different combinations of steel plate thickness with varying numbers of composite laminates in the backing plate in order to find the best protective combination when the 'synergetic' effect takes place (the ballistic resistance of the two-plate combination is better than the sum of the ballistic resistances of the plates). A significant weight saving was established for the standard 7.62 mm AP projectile but the synergism could not be established for an AP projectile with a higher length-to-diameter ratio. The critical factor for success of the best protective combination (exhibition of the synergism) was destruction of the projectile's steel core.

Report [Straßburger, 1996] described a series of ballistic tests using elongated projectiles (Kinetic-Energy or KE projectiles). These 17 mm-calibre 55 mm-length 214 g-weight projectiles were made of a tungsten alloy. The impact velocities in seven reported shots were around 1000 m/s against a hybrid target (appliqué armour). The facing plate of the target was made of ceramic (Al_2O_3) and the backing pate was made of Glass Reinforced Plastic (GRP). The composite plates had dimensions of 30 x 30 x 3.8 cm or 60 x 60 x 3.8 cm and the ceramic plates had dimensions of 15 x 15 x 4 cm. The GRP laminates were S-2 Glass/Polyester composites. The ceramic plates were mounted and glued into a steel frame confinement and the target was screwed to the steel frame. The yaw of the projectiles directly before impact was determined by high-speed photography. After impact at a velocity of 1090 m/s, which is higher than the ballistic limit velocity V50 (approximately 1070 m/s), the residual velocity of the projectile was observed to be approximately 640m/s. More substantial deformation of the backing plate and more developed delamination were observed for smaller GRP plates.

A less significant target factor is the sequencing of the composite's laminas. Ballistic tests in the impact velocity range from 0 to 600 m/s for the Twaron fibre system were reported in paper [Lim, 2002], using flat-nosed, hemi-spherically-nosed, ogival and cone-nosed (60°) projectiles launched by a gas gun. Single-ply and double-ply systems were tested and the test results (V50-values and the absorbed energies) compared. The absorbed energy was assessed as the difference between the impact and residual kinetic energies of the projectiles. The ballistic limit velocity (V50) was apparently assessed from the interception of the rising and falling zones of the absorbed energy curves. The V50 results exhibited an increase from a single to a double-ply system and the projectile shape was also shown to influence the outcome. The smallest increase increment was reported for tests with flat-nosed projectiles. This effect was attributed to the shear failure mechanism that requires less energy for projectiles of other shapes (impact by non-flat projectiles is likely to involve fibre stretching over a larger area around the impact point). It should be noted that this study employed unified equations for the absorbed energy assessment regardless of the projectile shape. However, the energy balance equations may need to be adjusted to the projectile shape because the plug kinetic energy probably needs to be taken into consideration for the case of impact with a flat-nosed projectile (the plug is clearly formed only for this case). For the same reason, the V50 assessments conducted in this paper for double-ply in-contact and spaced systems, should be treated with caution because the

projectile shape factor was not clearly defined for the spaced system due to a high likelihood of a non-zero yaw and obliquity at the second ply. The paper noted that the projectile shape factor for V50 diminishes for the double-ply system, when compared with the single-ply system. This effect is in agreement with the well-known trend of a diminishing effect of the shape factor with target thickness.

At a lower structural level, the treatment of fibres could be a factor in target response. The use of carbon fibres of two different types (a high failure strain and a low strength for the first fibre type and a lower failure strain and a higher compressive strength for the second) is reported in paper [Tanabe, 2003a], when manufacturing cross-ply laminates in order to assemble two-layer hybrid targets. Two such CFRPs with low-strength/high-strength (a high strength rear laminate – HR) laminates and high-strength/low-strength laminates (a low strength rear laminate – LR) were subject to impact by steel spheres of 4-5 mm diameter with impact velocities V_i from 150 up to 314 m/s (correspondingly, the incident energy E_i was from 5.8 to 25.5J). In-situ high-speed photography recorded different mechanisms of fracture for these two hybrid targets. For comparison, uniform laminates with mixed fibres of the two types were tested as well. The uniform laminate thickness was 2 mm, which was identical to the hybrid target thickness. The high strength uniform laminates have demonstrated an essentially larger damage area at the rear side of the target, when compared with the low strength uniform laminates (the damage area decreased and remained constant when E_i exceeded approximately 13J). Generally, low strength laminates demonstrated failure with a shear-plugging mode within this range of V_i. The HR targets exhibited a plugging failure mode and the high strength laminates and LR hybrid targets exhibited a fibre-breakage-in-tension mode of failure. Thus, LR hybrid targets appear to be suitable for high energy absorption purposes.

The same team as in [Tanabe, 2003a] conducted ballistic tests of CFRPs with plies of three different carbon properties [Fujii, 2002]. The tests were conducted with a higher range of impact velocities (from 500 to 1230 m/s). Steel 4 mm spherical projectiles were launched by a two-stage gas gun against 2 and 6 mm thickness samples. The carbon fibres used in these tests had the following mechanical properties: (1) a rather high stiffness and a very high strength (these characteristics provided a fair 2% failure strain); (2) a relatively low stiffness and strength (with approximately the same failure strain as in case 1 and; (3) a very high stiffness and slightly less strength than in case 1 (these characteristics provided a minimal failure strain). Different combinations of cross-ply laminates made from these fibres were used in the tests as 3-laminate assemblies. Absorbed energy was assessed as the difference between the impact and residual kinetic energies. The absorbed energy results revealed three basic curves with the highest values of absorbed energy (and the highest V50, respectively) for the samples with 2 laminates of type 1 (the highest strength and failure strain) at the rear side of the target. The choice of the front laminate did not affect the absorbed energy. An intermediate curve was found for samples with one laminate of the type 1 in the centre of the sample assembly. The choice of front and rear laminates did not affect the results unless the rear laminate was of the type 1. The lowest absorption energy values were registered for samples with laminates of type 3. The failure energy for the fibres was evaluated to be in the following order from maximum to

minimum: type 1 – type 2 – type 3. The assessments of the absorbed energy enabled the authors to conclude that the rear laminate is a key one from the viewpoint of energy absorption by targets. These results are in agreement with ballistic test results at lower impact velocities reported in the companion paper [Tanabe, 2003a].

6.4 Other ballistic performance criteria

Determination of the ballistic limit velocity is laborious. The critical aspect of ballistic performance is protection of behind-target objects, so observation of damage to a witness plate is widely used. A very simple criterion for the ballistic performance could be the depth of penetration (DOP) in the witness plate. DOP in ceramic targets as a measure of the ballistic performance was used in paper [Woodward, 1991a]. The DOP measure was also used in paper [Cimpoeru, 1996] in order to evaluate the ballistic thickness of a target backed by a witness block. The definition of ballistic thickness comes from the extrapolation of target thickness versus DOP dependence to the point DOP=0. Thus, two experimental points may be used for evaluating the ballistic limit thickness. Similarly, DOP in a steel witness block was plotted against impactor velocity in paper [Rupert, 1993]. Using this data, V50 could be evaluated. Simple rules for DOP of combinations of several targets (hybrid targets) were also considered in this paper. The influence of strength effects on DOP in targets made of conventional material subject to a direct hit has been observed using a numerical simulation, as reported in paper [Rajendran, 1998].

A comprehensive review on a variety of high-velocity impact issues is reported in paper [Backman, 1978]. The issues associated with impact were classified for thick, thin, and intermediate targets and the target materials considered were mostly conventional. The majority of the review dealt with the ballistic range of impact velocities. A minor part was devoted to hypervelocity impact. Several approaches were considered in order to link test results with predictive capabilities. Numerical modelling tools were considered in this review from the viewpoint of understanding the impact response in order to take the most relevant damage mechanisms into consideration. The purpose of the damage analysis and evaluation is improvement of predictive capabilities in order to use semi-empirical relations for the evaluation. Semi-empirical relations for thick targets are characterised mostly by the dependence of the penetration depth P on a variety of parameters in the following general form (usually a polynomial function):

$$P/D = f_1(V_i, D, h_t, \rho_t, m, s_t) \quad ,$$

here V_i is the impact velocity, D is the projectile diameter, h_t is the target thickness, ρ_t is density of the target material, m is mass of the projectile, and s_t is a stress limit characteristic of the target material.

Paper [Hazell, 1998] describes test results from the high-velocity impact of an alumina/aluminium target (appliqué armour) where the target assembly was complemented with a witness aluminium block that was used for the measurement of DOP. The criterion of ballistic performance was selected to be the Weight-Saving Factor

(WSF), which was introduced in paper [Yaziv, 1986]. The required mass to stop a projectile with the witness block is ρ_{ab} A_{ab} x (ρ_{ab} is density of the block material, A_{ab} is the area subject to impact, and x is the DOP in the witness block). The mass required to stop a projectile, including the mass of the target, is $\rho_T A_T h_T + \rho_{ab} A_{ab} x$ (ρ_T is density of the target material, A_T is the target area subject to impact, and h_T is the DOP in the target thickness). Then the WSF ballistic performance criterion can be written down as follows

$$WS = [\,1 - (\rho_T A_T h_T + \rho_{ab} A_{ab} x)/(\rho_{ab} A_{ab} x)] \times 100\% \quad .$$

A number of other criteria associated with ballistic performance can be deduced in a similar way. For example, ballistic efficiency criteria have been introduced in paper [Deutekom, 1999] for the assessment of ceramics. In addition to the WSF criterion, the total efficiency factor (TEF) could be considered:

$$TEF=(\rho_w P_0)/(\rho_t T + \rho_w P_x) \quad .$$

Here ρ_t is the density of the target material, ρ_w is the density of the witness plate behind the target, P_0 is the DOP for the witness plate (the DOP in the witness plate for control shot against the bare witness plate with the same impact conditions), P_x is the DOP of the witness plate with the target in front of the witness plate, and T is the target thickness. The Difference Efficiency Factor (DEF) could also be used for ballistic performance evaluation:

$$DEF = \rho_w (P_0 - P_x)/(\rho_t T) \quad .$$

The oblique penetration of alumina/aluminium targets (appliqué armour) has been considered in the paper [Yaziv, 1986]. Pairs of targets with the same thicknesses t, have been considered in this study. The total target thickness along the Line Of Fire (LOF) is $t_{LOF} = t/\cos(\theta)$, where θ is the obliquity angle. A depth of penetration (DOP) criterion was used in the study [Yaziv, 1986] with a mass efficiency that was calculated as follows:

$$E_m= (AD_{AL}\, DOP_{AL}\, V_i)/(AD_{tcer} + AD_{tAL} + AD_w\, DOP_w) \quad ,$$

where AD_{AL} is the areal density of an Aluminium semi-infinite block, DOP_{AL} is the DOP for this bare Aluminium block at a given impact velocity V_i, AD_{tcer} and AD_{tAL} are the areal densities of the ceramic and aluminium target components along the LOF, AD_w is the areal density of the penetrated material in the aluminium witness block and DOP_w is the measured DOP in the witness block. It was found that the ballistic performance of obliquely impacted targets was lower than that of normally impacted targets with the same areal density. A hydrocode analysis conducted in this work suggested that the ceramic was fractured by the bullet jacket, so the ceramic plate had no significant effect on penetration by the bullet core. This premature fracture of the frontal ceramic plate resulted in a reduction in the synergistic effect of the sandwich target.

More sophisticated criteria, such as the ballistic limit mass and the critical diameter of the projectile to be shattered by target, are used in hypervelocity studies. Paper [Destefanis,

1999] considered an advanced shielding for a spacecraft, consiting of two buffer shields made of composite materials. The impact velocity of fragments varied from 4.5 to 6 km/s. In this study, the ballistic limit characteristic was considered as a limiting mass of the fragment, for which a projectile with a lesser mass does not penetrate the shield. Oblique angle effects, which are not normally profound for conventional (metallic) shields, were observed to be significant within this range of velocities. Paper [Christiansen, 1999] considered hypervelocity impact against a complex composite structure that covers a crewmember space suit. The ballistic limit equations were derived for an impact velocity range of 4-8 km/s. In this paper, the ballistic limit was also treated as a critical diameter d_c of a particle hitting the composite structure, which can be just stopped by the target. The ballistic limit equations may be written down in the following general form:

$$d_c = C\,\rho^{-\alpha}\,V^{-2/3}(\cos(\theta))^{-\beta}\,, \qquad (6)$$

where ρ is the density of the projectile material, θ is the obliquity angle at the projectile-target encounter, and V is the impact velocity. A similar criterion has been derived in paper [Turner, 2001] for shields containing honeycomb and insulating materials. For a bumper shield with a rear wall target spaced by distance S, the ballistic limit relation for the case of penetration of the wall target involves the bumper thickness t_b, the wall target thickness t_w, densities of the bumper and the wall ρ_b, ρ_w, and the strength of the wall σ. Such a relation is known as a Whipple Shield Ballistic Limit equation that can be presented in the following general form:

$$d_c = f_w\,(t_b\,,\, t_w,\, \rho_b,\, \rho_w,\, V,\, \theta\,,\, \sigma\,,\, S)\quad .$$

This equation is usually used for monolithic bumpers and in paper [Lambert, 2001] it was also used for sandwich panels. The Whipple Shield equation can be reduced to equation (6) in the lowest range of meteoroid impact velocities (when the impact velocities are less than 1-3 km/s). A description of the Whipple Shield principle together with details of the equation derivation can be found in paper [Christiansen, 2001], where this equation was exploited for several composite and hybrid bumpers.

For thin targets, the study of penetration effects (evaluation of the absorbed energy) and an evaluation of the residual velocity V_r is of major interest. Therefore, the baseline semi-empirical relation is linked with the assessment of the ballistic limit velocity V50, for example, in the following form taken from the review [Backman, 1978]:

$$V50 = f_2\,(h_t\,,\, D,\, \theta)\quad ,$$

where θ is the obliquity angle, h_t is the target thickness, and D is the projectile diameter. In addition, for hypervelocity impact, the residual mass of the projectile m_r may be an important factor and expressed in the following form taken from the same review:

$$m_r = m - m_C\,(\rho_d\,h_t\,A_d/m)^{b_1}\,(V_i/C)^{b_2}\,(\rho_d\,h_t\,A_d/m_0)^{b_3}\,,$$

where A_d is the areal density, ρ_d is the density of the projectile material, and m_0, C, b_1, b_2, b_3 are constants. Again, when necessary, the strength parameters may be included as well (it should be noted that within the hypervelocity range of impacts, strength factors are commonly neglected).

The resistances of targets to blunt and conical projectiles are quite different. A range of V50-equations has been derived in order to relate the data for both projectile shapes. For example, an equation linking the ballistic limits V50 was stated in paper [Backman, 1978]:

$$V50(\text{blunt})/V50(\text{sharp}) = \exp(-\, b_4 \cdot h/D) + A \cdot (1 - \exp(-\, b_5 \cdot h/D) \ ,$$

where h is the target thickness, D is the projectile diameter, and A, b_4, and b_5 are constants. The hole diameter again can be seen to be a parameter of interest. A general formula (see [Backman, 1978]) for the critical hole diameter D_C can take the following form:

$$D_C/D = 1 + f_3\,(V_i, h, D, s_t, \rho_t\, , \rho_d\,) \ ,$$

where V_i is the impact velocity, ρ_t is the density of the target material, ρ_d is the density of the projectile material, and s_t is one of the stress limit characteristics of the target material.

It has been shown above that a number of the input parameters may be of importance for description of the results of impact and for evaluation of the appropriate resulting (output) parameters. For composites the number of these input parameters may increase, especially for some specific types of composite materials (e.g., materials with a strong anisotropy), and may involve structural parameters such as the strengths of constituents, parameters of manufacture, etc. Obliquity issues (especially in the ballistic range of impact velocities) are rarely studied. The influence of encounter parameters, such as the yaw and pitch, has very rarely been studied. Available literature notes a requirement for advanced models of conventional materials in order to model ballistic impact. Such a requirement is more urgent for the modelling of composite materials. It should be noted once again that damage resistance data are sensitive to the target material and the range of impact velocities. Thus, there are no universal semi-empirical ballistic limit relations for the whole range of target materials and velocities of impact. For example, in the hypervelocity range of velocities (2-7 km/s) for impact against carbon/PEEK composite targets, a study, reported in paper [Lamontagne, 2001], has demonstrated that the impact damage is insensitive to projectile material density and almost insensitive to the impact obliquity angle. However, it is sensitive to the projectile diameter and velocity of impact. Within the ballistic range of velocities, however, the sensitivity to the obliquity angle is known to be high.

A very urgent task, which is associated with development of novel weapons and the use of improvised explosive devices, is to evaluate the performance of the combined effect (synergism) of blast and fragmentation. An attempt to derive a criterion for target performance against blast/fragmentation effects was reported in papers [Resnyansky, 2004a]. However, this field is not widely studied at present.

6.5 The influence of the shape of projectile

Among the factors affecting the ballistic limit velocity V50, the effect of the projectile's shape is obvious and is noted in many papers. For example, ballistic testing results are reported in paper [Buchar, 1999] for several types of wood targets. 7.62 AP projectiles, STANAG-290 fragments and ball projectiles were used in these tests. It was found that the lowest V50 was achieved for AP projectiles and the highest V50 was observed for ball projectiles. It was also found that the projectile residual velocity depends almost linearly on the target thickness.

Several shapes of projectile have been analysed in paper [Nandlall, 1999] including ball projectile and Fragment-Simulating Projectile (FSP) (this projectile has a chisel-nosed shape). Thicknesses of the composite targets varied from 2 to 12 mm. Two sets of light screen detectors or a radar system were used for the measurement of the impact (V_i) and residual (V_r) velocities. The ballistic limit velocity (V50) was obtained from the Lambert-Jonas equation with an exponent of 2 (equation (4)), using impact and residual velocities. The V50 values evaluated for impact by FSP were found to be lower than the V50 values for impact by ball projectiles. The ballistic limit velocity for impact by ball projectiles was found to be higher in the case of two separated targets, when compared with the case of one target with the same equivalent (combined) thickness. This result is somewhat in contradiction with the results reported in the papers [Partom, 2001; Radin, 1988] for flat and conically tipped projectiles. This contradiction may be caused by the assessment method of V50 values from the experiments or from the nature of the targets (which are made of a composite in this study, in contrast to conventional and appliqué armour targets in the papers [Partom, 2001; Radin, 1988]) and the shape of the projectile (which is ball-shaped in this study, in contrast to the flat and conically-nosed shapes in the papers [Partom, 2001; Radin, 1988], which may result in more pronounced plugging).

A comparison reported in the paper [Cantwell, 1990] shows that the perforation energy of a composite target (a definition of the perforation energy along with review of this paper was outlined in subsection 5.1) was an order of magnitude higher for impact by a spherical projectile than for a cone-nosed projectile. The delamination zone in a target material was also much larger for the case of impact by a spherical projectile. Damage mechanisms for carbon/epoxy composites subject to impact, which were listed in this paper and then included in an analytical model, are; crack propagation, fibre failure, petalling, delamination, hole enlargement, and friction. The model developed in the paper claimed that fibre breakage occurs with a single fracture mechanism during static indentation and with multiple mechanisms through-the-target-thickness during ballistic impact. A comparison of perforation energies for targets made of Kevlar/ epoxy and carbon/epoxy composites is reported in paper [Zhu, 1992a]. This comparison on the basis of equivalent areal density showed a better ballistic performance (a higher perforation energy and ballistic limit velocity) for the Kevlar-fibre composite. The carbon/epoxy composite (CFRP), when compared with the Kevlar/epoxy composite (KFRP), showed lower delamination after the impact. The damage mechanism of the CFRP targets was petalling,

and the damage and deformation mechanisms of the KFRP targets was bulging. The paper stated that strain-rate and vibratory effects observed were negligible in this study.

A study of the influence of projectile shape on the process of energy absorption is described in paper [Mines, 1999]. Projectile diameters were 7.6 and 10 mm with projectile masses of 6 and 12 g, respectively. Projectiles included balls, hemi-spherically nosed projectiles, flat-nosed projectiles, and cone-nosed projectiles. The targets were fully clamped with target dimension of 20 x 20 cm and the material was a woven glass polyester laminate with a number of laminate thicknesses (6, 12, 24 ply). A smooth bore 10 mm powder gun and a 7.6 mm rifled gun were used to fire the projectiles. Impact velocities varied up to 570 m/s. The objective of the paper was to compare impact perforation energy for projectiles of different forms. Static tests were also conducted along with ballistic tests. The paper claimed that 20 x 20 cm is the smallest possible target dimension that will allow localised ballistic damage to be assessed without any interaction with the target boundaries. In this study, it was shown that the energy absorption that occurs locally (energy absorption in this case is associated with the shear damage mechanism) was the principal component for thin targets (6-ply targets). Energy absorption associated with delamination damage dominated for the 12- and 24-ply targets. The dynamic enhancement factor was defined as the ratio of the dynamic to static perforation energy. It was shown in the study [Mines, 1999] that this factor was greatest for the target response to flat-ended projectiles and least for the following two conditions: i) cone-nosed projectiles in the case of the thickest 24-ply targets; and ii) hemi-spherically nosed projectiles in the case of 12-ply targets. Thin targets demonstrated a high scatter in values of this factor.

Ballistic tests of aramid-fibre (Twaron) fabric composite systems were reported in paper [Tan, 2003]. Impactors were flat-nosed, hemi-spherically-nosed, ogival and cone-nosed (60°) projectiles launched by a gas gun with impact velocities in the range from 0 to 600 m/s. Ballistic limit velocities (V50) were assessed by the 50% rule (a 50% chance of penetration), using interpolation of the data obtained from the tests. The V50-values were found to be 159, 100, 76, and 58m/s for the hemi-spherically-nosed, flat-nosed, ogival and cone-nosed projectiles, respectively. The energy absorbed (assessed as the difference between the impact and residual energies) increased with impact energy up to a maximum value and then decreased to a constant limit. This limiting behaviour could be attributed to the reduction of the elastic energy with impact velocity so that, at velocities much higher than V50, the absorbed energy is almost entirely damage energy. The response of targets to sharper projectiles demonstrated less energy absorbed due to target damage rather than strain energy transfer to the target. The largest absorbed energy was achieved for targets impacted by hemi-spherically-nosed projectiles and the least absorbed energy for targets impacted by ogival and cone-nosed projectiles. Post-mortem examination of the target fabric found that hemi-spherically-nosed projectiles damaged samples mainly through rupture of yarns when stretching them (progressive sample damage up to fracture through shearing at high impact velocities). Damage due to impact by ogival and conical projectile was due to a significant bowing mode of fracture. Flat projectiles penetrated mainly by shearing and stretching yarns. The smallest increment of absorbed

energy was reported in this study [Tan, 2003] for flat-nosed projectiles. This was attributed to a shear failure mechanism of the target because this mechanism requires less energy than deformation and damage involving fibre stretching from a wider area around the impact point for projectiles of other shapes. It should be noted that the evaluation of absorbed energy conducted in this paper ignores the kinetic energy of the plug that is clearly formed only for the case of impact by flat-nosed projectiles. It is also worthwhile noting that the V50-values obtained in this study for double ply in-contact and spaced composite systems, should be treated with caution because the projectile shape factor cannot be clearly defined for the spaced system due to possible yaw and obliquity when impacting the second ply. The paper noted that the projectile shape factor for V50 diminishes for the double-ply system and this is in agreement with the well-known trend of a reducing influence of the shape factor with increasing target thickness.

Tests of Spectra Shield fabric specimens are reported in paper [Tan, 2005]. The range of impact velocities varied from 0 to 400 m/s. 15 g mass 12.6 mm calibre projectiles had the following shapes; flat-nosed, hemi-spherically-nosed, ogival and conical (60°). Impact by flat-nosed and hemi-spherically-nosed projectiles resulted in target damage in the form of generator strips (parts of target plies forming strips that split along the fibre direction without delamination within the strips) along the whole length of the sample (the strips were smaller for the hemi-spherically-nosed projectiles). Locally, filaments in the impact area of the target were broken through shearing when impacted by flat-nosed projectiles and through filament stretching when impacted by hemi-spherically-nosed projectiles. In this study, delamination was observed in a rhombic pattern composed of the generation strips. Delamination was minimal under impact by the ogival and conical projectiles.

Paper [Pierson, 1993] described a study of the penetration of a carbon/epoxy laminate by ballistic projectiles with flat or conical noses. An analytical model was suggested and validated, in which absorbed energy was decomposed into dissipated energy, energy associated with local or drag effects, energy due to global bending, and either the kinetic energy of a plug (for the case of impact by the flat-nosed projectile) or the frictional projectile-target energy (for the case of impact by the cone-nosed projectile). According to the model, at an impact velocity of 30 m/s, energy was noticeably absorbed within a 5 mm range from the indentation spot on impact by the flat-nosed projectile and within a 20 mm range on impact by the cone-nosed projectile. Dissipated energy was the major component of absorption energy from the analytical analysis.

Paper [Bartus, 2005] reports on tests of GFRPs with randomly oriented long fibres approximately 25.4 mm in length. The effect of the mass and shape of a projectile on the failure mechanism in the target at impact and the energy absorbed by the target was studied. Steel cylindrical projectiles used against composite targets in these tests had the following configurations: i) 25 and 50 g flat-nosed projectiles; ii) 25 and 50 g cone-nosed projectiles; and iii) 100 and 160 g flat-nosed projectiles. For each shape, the mass effect was expressed as an exponentially decreasing dependence of the ballistic limit velocity on the projectile mass. For the case of impact by cone-nosed projectiles this dependence was less pronounced. Within the impact velocity range from 40 to 140 m/s, no noticeable rate and

projectile mass dependencies were noted when tracking the target response through both high-speed photography observations and post-mortem SEM examinations. The primary damage mechanism of a target subject to impact by a flat-nosed projectile was shear. Crack branching in targets was much more extensive for the target response to impact by a cone-nosed projectile. Away from the impact spot, the damage mechanism in the composite target was planar cracking with the cracks propagating along the fibre directions, where a high degree of coordination with the fibre directions was observed. The energy dissipation (the damage energy) was 27% less for targets subject to cone-nosed projectile impact, when compared with flat-nosed impact, but the damage was larger and accompanied by more developed cracking.

In the hypervelocity range of impact velocities, projectile energy is more dominant than the projectile shape. Nevertheless, the impact energy space concentration can still vary and some influence of projectile shape can be found in this velocity range as well. For example, hypervelocity impact against Kevlar fabric was considered in paper [Hayhurst, 2001]. The influence of projectile momentum on the damage (the perforation opening) caused by impact was observed. The shape factor due to impact by a compact projectile and by a shaped charge jet was reported and the shaped charge jet was observed to produce more penetration.

Due to the wide use of sandwich and cellular materials in helicopters, the response of these materials to ballistic impact is an important issue. Unfortunately, publications in this field are quite rare. Foam-filled sandwich composite tests are reported in paper [Skvortsov, 2003] (see review of the energy partitioning for this structure in subsection 6.2). This material was subject to impact by projectiles of three different nose shapes: i) hemi-spherical; ii) a low-cone (90°); and iii) a tall-cone (~38°). Quasi-isotropic and orthotropic lay-up glass/epoxy composites were used as the face and back sheets for this sandwich material. Dependence of the absorbed energy on the projectile shape was assessed during the testing. This dependence was more pronounced for the impact of sandwich material when the orthotropic laminate face-sheets covered the foam core of the target material. It was observed that this dependence was moderate for target material that had quasi-isotropic laminates as the face-sheets. When the sandwich samples with orthotropic lay-up face-sheets were impacted at a velocity of approximately 70 m/sec (V50 was found to be 40 m/s in this case), the absorbed energy increased by 10-20% when the tall-cone projectile was replaced by a low-cone projectile. The absorbed energy increased by 20-30% when the low-cone projectile was replaced by the hemi-spherical projectile.

6.6 The influence of manufacturing/structural conditions and pre-load

Under LVI conditions, material response may be determined using instrumented testing machines. However, under ballistic impact, such measurement is sometimes impossible due to the short duration of the impact process. Therefore, assessment of the integral response of a target under ballistic impact is common and it usually takes the form of evaluation of the absorbed energy, using either measurement of the residual velocity of a penetrating projectile or direct V50 measurements. Embedded gauges and high-speed

photography are becoming routine instrumentation tools, allowing the in-depth analysis of damage mechanisms under ballistic impact. The manufacturing conditions of a composite target are very important for evaluation of impact resistance to low-velocity impact, as was shown in subsection 5.5. Due to the short process duration for ballistic impact, a small area of a composite target is involved in the target response. Therefore, it could be expected that manufacturing factors are not as influential for ballistic impact as for low-velocity impact. However, the local response at the point of impact and localised manufacturing features can still be important for the target response to ballistic impact.

Comprehensive static and ballistic testing of Kevlar targets has been carried out in the paper [Zhu, 1992a]. Conically nosed 60° projectiles and indentors that had diameters of 9.5 and 12.7 mm were used. This study concluded that global and shear stiffness response is important in quasi-static tests (from the viewpoint of the influence on the load-displacement curves). However, the stiffness response is of considerably less importance in ballistic tests (from the viewpoint of the influence on the ballistic limit velocity and the delamination area). Local deformation (matrix compression and fracture) and fibre breakage were found to be the major absorption mechanisms for these impact conditions. It was observed that pre-made delamination in the target, a variation in the fibre concentration of the target material, and material lay-up variations, affect static results. However, these factors are of minor importance for the impact absorption energy of target material evaluated under ballistic impact tests. Overall, the ballistic performance of the Kevlar composite was better than the performance of aluminium on an equal areal density basis. A companion paper [Zhu, 1992b] describes an analytical model that considers three successive stages of the perforation of Kevlar composite targets; indentation, perforation, and exit. This paper is based on: i) a model-design analysis, using representations of the mechanical process (high-velocity impact) deduced from impact tests; ii) development of the model, employing these representations; and iii) validation of this model, using the same test results that were used for development of the model. Thus, the study is based on the same test data for development and validation of the model, and therefore, the results should be accepted with caution.

The paper [Tanabe, 2003a] includes a discussion on the impact response of CRFPs made from plies with different surface treatments. The composite targets were cross-ply low-strength and high-strength 2 mm laminates (details of the target material characteristics were reviewed in subsection 6.3), and woven fabric laminates. The targets were tested over a range of impact velocities from 150 to 310 m/s. The tests did not find any essential difference in the absorbed energy and damage area for the woven and cross-ply laminates. The plies of the woven fabric laminates were treated in order to increase the interlaminar shear strength (ILSS). Two basic types of laminates were analysed in this study; laminates with low ILSS (below 30MPa) and laminates with high ILSS. The total impact energy was successfully absorbed at an impact velocity V_i lower than 150 m/s for the low-ILSS laminates. In contrast, penetration occurred at the same V_i for the high-ILSS laminates. According to this study, the V_i range in which the surface treatment can be effective is dependent on the target thickness. Stress measurements with embedded constantan gauges at impact velocities from 150 up to 1300 m/s were reported in paper [Tanabe,

2003b]. Stress analyses showed that fibre strength is a critical determinant of the stress level at impact. It was observed in this study that for low-strength CFRPs (regardless of the structure, which is either cross-ply or woven), the increase in stress was much more significant than for the high-strength CFRPs. For woven laminates with the low ILSS, the stress and strain at impact were lower than for the high-ILSS laminates.

Ballistic impact tests against composite targets made of CFRPs with cross-ply and woven (five-harness cloth) structures are reported in paper [Fujii, 2002] for composite samples of 2 and 6 mm thickness. The targets were impacted by steel 4 mm diameter ball projectiles in the velocity range from 500 to 1230 m/s. The test results showed no difference in absorbed energy for these two composite structures. The absorbed energy was calculated as the difference between the impact and residual kinetic energies of the projectile. It was concluded from these observations that the composite structure (in this range of velocities) has no a significant effect. It should be noted that this conclusion should be restricted to the investigated structures and the chosen target thicknesses. In general, as seen from this study, weave variation does not significantly affect the absorbed energy. Obviously, the damage mechanism is associated with the local character of deformation under ballistic impact. The fibre orientation for these composite structures was mainly perpendicular to the impact direction (the harness number is five for this woven structure, this means that the fibre orientation varies only after five cross-passing fibres in this laminate, resulting in fibre intersection between cross-passing fibres). Therefore, the structure variations for these composites are too small for the damage mechanism to be affected during the short time of the target-projectile interaction.

However, when the composite structure varies at a low level (on the micro-level), then the local character of deformation can be affected by the structure variation. For such structures, the influence of the composite structure on V50, or the absorbed energy, increases. Plain weave and satin weave structures of carbon/epoxy composite were analysed under ballistic impact conditions in paper [Hosur, 2004b]. The influence of the structure variation on the ballistic limit velocity was studied. Generally, a plain weave structure involves frequent change of the fibre orientation (the harness number is one). The satin weave structure is a smoother structure (this structure is comparable with the five-harness cloth considered above), resulting in a smaller number of fibre intersections (the fibre orientation changes fewer times, when compared with the plain weave structure). In this study [Hosur, 2004b], fragment-simulating projectiles were used in ballistic tests and the composites, which were stitched and unstitched with a Kevlar thread, were tested for varying stitch-grid sizes. For an unstitched sample, V50 was 38% higher for thin satin samples (the sample thickness was 3.5mm) and 13% higher for thick satin samples (the sample thickness was 15mm), when compared with plain weave composite samples. The dominant mode of fracture was flexure for the satin samples, which resulted in a larger damage area (hence, in more absorbed impact energy), when compared with the damage and absorbed energy for the plain weave composite samples. Shear was the major damage mechanism for the plain weave composite structures. The architecture of the weave influences V50 more for thick samples than for thin ones. For a small size of the stitch grid, the damage area was larger when the projectile hit the edge of

the grid and this effect diminished for a larger grid. The ballistic limit velocity V50 was 37% higher for an unstitched sample and it was 59% higher for a sample with large stitch-grid, when compared with V50 for a sample with small stitch-grid.

Ballistic tests, using the same facility and test set-up are reported in paper [Hosur, 2004c] for targets made of unstitched and stitched plain weave composites. The thickness of the samples was 3 mm and two stitching configurations were used with stich-grid sizes of 25.4 and 12.7 mm. The reported increase in the ballistic limit velocity for stitched targets was just 2 and 5% for these two stitching configurations (25.4 and 12.7 mm-grid sizes, respectively), when compared with V50 for the unstitched samples. Keeping in mind the method which was used for the calculation of the ballistic limit velocity from impact and residual velocities (the formula (4) discussed in subsection 6.2), and a significant scatter in the V50-evaluation (more than 10%), it should be noted that the V50 change for the 3 mm-thickness samples was almost negligible. However, V50 change increased significantly with larger sample thicknesses when compared with the results of the companion paper [Hosur, 2004b].

The dependence between impact and residual velocities for normal impact incidence is reported in papers [Gu, 2004; Gu, 2005]. Composite targets made of 3D-braided aramid (Twaron) fabric were impacted by 7.62 mm military rounds. An FEM-model was developed and verified against the test results. A reduction of the absorbed energy at high impact velocities was evident from the data for this 3D-braided composite material.

Structural variations in sandwich and cellular materials can be more significant than for composite materials. Therefore, the influence of the structure of foam materials on the absorbed energy and V50 under ballistic impact is a much more complex issue than for composite material. High-velocity impact tests against Tricell™ honeycomb material have been described in paper [Vaidya, 2003]. In this paper, the honeycomb material (with a paper core) was used in the following forms: i) a pure core; ii) a honeycomb that was fully filled with polyurethane foam; and iii) a honeycomb that was partially filled with a syntactic foam. Combinations of materials with face-sheets made of a carbon/epoxy laminate completed the range of samples tested. Wooden 50 g weight and 38.1 mm diameter cylinders were used as projectiles (the impact velocity varied from 0 to 100 m/s). These projectiles impacted sandwich samples that had a thickness of 25.4 mm and in-plane dimensions of 127 x 127 mm. The samples were simply supported during the tests. Shear was reported as the main damage mechanism. The paper noted a large delamination of the back face sheet, but this should be taken with caution because of obvious boundary effects. With the relatively small sample dimensions and relatively low impact velocities, there may be enough time for shear waves to reach the boundary during the projectile-target interaction. Interaction of these waves with the free lateral boundary may promote delamination. In the presence of the free lateral sides of a sample, a tendency of the cellblocks to shear up to the edge of the sample was observed. This deformation pattern was diminished (however, it was not eliminated completely) for samples confined with face-sheets. For samples filled partially with syntactic foam, the damage at the front face-sheets was reported to be larger than for samples filled in fully with polyurethane foam.

This damage behaviour was attributed to the high stiffness of the syntactic foam. It was observed that the ballistic limit velocity for targets made of the fully-filled core increased by 73%, when compared with V50 for targets made of the unfilled core.

Paper [Christopherson, 2005] describes high-velocity impact tests against sandwich materials made of a foam-filled honeycomb core. The sandwich targets were covered on one or two sides by laminate face-sheets. The test results for the honeycomb-core sandwich targets were compared with each other and with test results for a 4-ply laminate target (a multiple-ply composite target). Steel 16 g and 12.7 mm diameter projectiles were used in the velocity range from 80 to 150 m/s. The samples (127 x 127 mm in the in-plane dimensions) had several configurations: i) 15.9 mm foam-filled core covered by carbon fibre 4-ply laminates on both sides of the target; ii) 25.4 mm foam-filled core covered by laminates on both sides; iii) 25.4 mm foam-filled core covered by laminate on one side; and iv) 4-ply laminate samples. The absorbed energy was assessed as the difference between the impact and residual energies. The samples with foam core covered by laminates on both sides showed a higher impact resistance, which increased with the core thickness. For the sample with the thickest core, the absorbed energy did not reach a maximum in the given range of velocities. For the sample with the 15.9 mm core the absorbed energy reached a maximum of 56 J at approximately 89 m/s impact velocity which appeared to be a critical velocity (the impact velocity that provides maximum absorbed energy). When the impact velocity exceeded the critical velocity, the damage area increased and the absorbed energy decreased. This dependence of the damage and absorbed energy on the impact energy is typical for all of the samples for which a maximum absorbed energy was achieved. With higher impact energy the maximum absorbed energy was observed to be higher. The damage mechanisms noted in [Christopherson, 2005] included fibre breakage and matrix failure, which occurred in the face-sheet laminates. Interface delamination between the face-sheets and the core was observed as well. The results demonstrated that for one-side-covered laminates the critical impact energies (the impact energy that corresponds to the critical impact velocity) are all close to each other, with a slightly higher value for the case of the face-sheet laminate facing the projectile. The critical absorbed energy (the absorbed energy evaluated for impact at the critical velocity) was observed to be lower for the one-side-covered laminates than for samples covered on both sides. The 4-ply laminate target (the solid composite target) demonstrated relatively low absorption capacity with a maximum absorbed energy of 28 J at a critical velocity of approximately 63 m/s. As seen from this study, in contrast to the higher damage localisation of composite materials at higher impact velocities, the damage in sandwich and cellular materials may be more severe with an increased impact velocity.

The use of microcellular foam has been reported in paper [Colombo, 2003] for protection against meteoroid impact. The structural response of a sandwich material with a core made of this foam has a compaction plateau stress which is three times higher than the compaction stress of conventional macrocellular foam. When using this sandwich material in a Whipple Shield, the benefit of the material increased with increasing impact velocity because the absorption capacity increases with the stress. The weight saving capacity of this material is high (the bulk density of the foam is 0.36 g/cm^3). A similar idea was the

basis of paper [Li, 2004] where it was demonstrated that porous materials exhibit a high resistance to hypervelocity impact. The effect of porosity is also significant for a target responding to impact in the ballistic range of impact velocities. For example, the paper [Baucom, 2004] describes results of ballistic tests against a cellular 3D-woven system. 19 mm diameter cylindrical steel projectiles were fired by a smoothbore propellant gun in the velocity range from 100 to 240 m/s. Fibre concentration and the porosity fraction were the variable parameters of the study. The absorbed energy characteristic (the energy was normalised by the areal density) showed no sensitivity to the fibre concentration, but this characteristic was found to be sensitive to porosity (a higher porosity in the target material resulted in greater absorbed energy).

Ballistic tests of targets in a pre-loaded state are very rare because of the difficulties in setting up a target. A study reported in [Olster, 1972] dealt with the ballistic testing of pre-loaded composite targets. The objective of this work was to determine the 'threshold' tensile stress σ_{th} at which catastrophic failure of a sample occured during impact. Graphite/epoxy and boron/epoxy composite samples with different lay-ups were primary targets and several tests were also carried out with glass/epoxy composite targets. The projectiles were Armour Piercing (AP) 7.62 and 12.7 mm rounds that impacted the targets at normal incidence. The 7.62 mm-AP projectiles were fired at velocities of approximately 840 and 380 m/s and the 12.7 mm-AP projectiles at a velocity of 914 m/s. The targets were pre-loaded with tensile stresses equal to 30 and 70% of the ultimate tensile strength σ_u of the materials tested. The residual tensile strength after impact σ_t was also measured. This work has revealed that the 'threshold' stress σ_{th} was typically as much as 90% of σ_t for both boron/epoxy targets and graphite/epoxy targets. Only small σ_{th} variations due to the change of the velocity of impact, projectile calibre, or pre-load were observed. The major reason for the σ_{th} variations was the material lay-up variation. A visual inspection of targets after impact revealed extensive delamination for the glass-epoxy targets. Limited delamination was observed for the graphite/epoxy samples, and almost no delamination was reported for the boron/epoxy targets.

6.7 Damage modelling and kinetic models

Damage modelling for ballistic impact has the same objective as modelling for low-velocity impact (see the literature review in subsection 5.6). However, under LVI conditions the main object of the analysis is the target, so the analysis in the LVI case concentrates mainly on the issues of: i) how much energy the target can resist); and ii) the extent and character of the damage done to the target. In the case of high-velocity impact, the main objectives appearing in the literature are i) the target damage and the residual strength of the target material; and ii) the projectile's residual energy. At very high and hyper-velocities of impact one more issue of concern is the kinetic energy of the behind-target (behind-skin) debris. High energy of impact may also raise the issue of the target/skin/shield action against the projectile. This point is important for a behind-skin target because projectile fragmentation and damage influences the behind-skin distribution of debris and, thus, affects the damage of secondary structures/ targets. For example, a theoretical model suggested in paper [Grady, 2001] presented a mechanism for

projectile fragmentation. This study concentrated on combined behind-target effects of projectile-target debris in the hypervelocity impact range. Shell fragmentation of HEI rounds was considered in paper [Anderson Jr., 1999a] (the results of this study were reviewed in subsection 4.6). The effect of a ceramic plate in a hybrid ceramic/aluminium target (appliqué armour which has been reviewed in subsection 6.4) on the damage to a jacketed bullet has been taken into consideration in the paper [Yaziv, 1986]. Projectile deformation was considered in paper [Resnyansky, 2002c] when evaluating the residual velocity with a hydrocode for the penetration of CFRP targets. However, projectile deformation and damage are frequently ignored for ballistic impact of composite targets because the hardness of the projectile is usually much higher than the hardness of the target.

Hydrocode modelling is a very popular tool for the damage analysis of composite targets subject to ballistic impact. When modelling with commercial hydrocodes and using the Lagrangian approach, a large distortion of the finite-element or finite-volume mesh of the target's numerical model is inevitable in the ballistic range of impacts. The standard existing option is to delete (erode) the elements at a pre-selected 'failure' strain. This approach is purely numerical because the 'failure' strain used in the hydrocodes is poorly defined from a validation viewpoint. In addition, strain is not the only factor affecting the integrity of a composite material. However, this option is widespread because of its simplicity. For example, this approach was used in paper [Lim, 2003] where a semi-empirical monotonically decreasing dependence of the failure strain on strain rate was applied. The major disadvantage of the erosion approach is violation of the conservation laws. An advanced approach is the explicit introduction of cracks (free surface boundaries) into the numerical mesh when a failure criterion is met. Such an approach has been described, for instance, in paper [Resnyansky, 2002b]. In doing so, the failure criterion could be of any physical nature and might be linked with the current state of the material or with its history. A damage accumulation criterion was used in [Resnyansky, 2002b] for simulation of brittle-type damage. The complexity of this approach for the case of composite materials would be the mesh-dependence of a numerical solution (primarily, the grid orientation dependence of the crack direction). Such a dependence is not easy to link with the strong anisotropy of composites. Micro-structural modes of failure, multiplicity of the modes, and their alignement to crack orientation may be in disagreement with the chosen mesh-orientation. As a result, the simple erosion approach remains the most popular method of calculating damage when modelling the ballistic penetration of composites. Several examples of the usage of this approach can be found in papers [Duan, 2005b; Gu, 2005; Her, 2004; Lim, 2003; Robbins, 2004].

Unfortunately, most commercial structural and hydro-codes are not well tuned to the response of specific composite materials. The models employed by most codes only roughly approximate the shock-related processes in composites and, especially, the damage. Many attempts have been undertaken to enhance the models and to formulate new approaches for a description of composite behaviour. The simplest way to desribe damage progress in composites is the degradation of the elastic modulii that are used in the classic anisotropic elasticity theory. For example, the anisotropic linear elasticity theory

has been employed for DYNA3D modelling of a glass-fibre laminate in paper [Belingardi, 1998] where a gradual degradation of the elastic modulii is used to model the post-failure behaviour of the composite. The load-deflection response of a composite target during drop-weight LVI testing was simulated in the study. This study attempted to take into account the elements that were lost during the erosion, allowing the absorbed energy to be evaluated numerically. The authors obtained good agreement with the load-displacement curves from quasi-static tests, but some discrepancies were reported for dynamic tests. This was explained by the non-elastic behaviour of the composite before failure, which cannot be simulated with the elasticity theory used.

Paper [Van Hoof, 1997] described the modelling of a high-velocity impact of an aramid fibre-reinforced (AFR) composite plate by a fragment-simulating projectile. The composite material was presented as a set of anisotropic layers with properties (the elastic modulii) that fit to the properties of the AFR composite. The damage failure criterion used in this simulation described delamination between the layers. The anisotropic material model allowing for damage, which was described in report [Matzenmiller, 1991], was used in the calculations. The elastic modulii of this model are damage dependent (similar to the stiffness-degrading models). Damage inside the composite layers was associated with a critical strain (the parameter governing the degradation of the modulii) and inter-layer delamination was initiated at a critical stress.

Papers [Gu, 2004; Gu, 2005] reports on a structural fibre inclination model related to the transformation analysis [Bahei-El-Din, 2004] described in subsection 5.6. Cells, which are not associated with the finite elements of the numerical grid, are generated in a similar fashion for a 3D-braided composite (aramid fabric). Parameters for these cells are actually model parameters that are pre-selected and they do not have physical or numerical-mesh meaning (they could be thought to be parameters of a meso-structure generated by the model). The stress state is evaluated from a quasi micro-structural consideration of an equivalent cell consisting of four ‘effective’ laminas (each lamina contains a yarn in one direction) that are inclined in four directions for every cell. From the inclination angles and elastic properties of fibres and the matrix, equivalent elastic properties can be found, which have to be in agreement with the macro-mechanical properties of the composite. This modelling algorithm was implemented in paper [Gu, 2005] as a user-defined subroutine in the DYNA hydrocode. The erosion algorithm for finite elements was used in this implementation as the numerical failure mechanism. In this paper, the model was applied to the case of ballistic impact of a composite by a 7.62 military round. The algorithm allowed the authors to manipulate the number of cells, deactivating them in accordance with a failure criterion and this deactivation occurred dynamically during the projectile penetration, depending on the micro-structural state of the cell. Stress-surface envelopes (the limiting stress surfaces in the stress space) were used as the failure criteria for fibre breakage, matrix cracking, and general compressive failure (which possibly corresponds to delamination). For each type of the failure mechanism selected, the corresponding elastic modulii and Poisson ratios were set to zero.

The description of damage kinetics by constitutive models is becoming a common practice. For example, paper [Randles, 1992] describes the derivation of a constitutive model for a damagable composite material. The material was described with the help of a homogeneous transversely isotropic material model which contains a number of parameters that are responsible for the description of a continuum net of cracks in the in-plane and transverse directions. Degradation of the elastic modulii is controlled by these parameters. The constitutive (kinetic) equations, which describe the evolution of the parameters, were tabulated. High-strain data on the flexure of composite samples at a number of strain rates were simulated using this model. It should be noted that the model validation conducted in this study is questionable since the parameters of the model have been, probably, fitted to the validation data.

Another paper [Jiang, 1997] describes a finite element simulation of composite laminates using a similar approach. A damage accumulation theory of an incremental type was used where a degradation rule for the change of the elastic modulii with the degree of damage was introduced. In this study, an effective strain was considered as the auxiliary variable used to qualify the matrix fracture, fibre breakage, and delamination. A procedure of node subdivision (duplication) was introduced in order to simulate explicitly the fracture process. Fracture onset occurs on fulfilment of a criterion that is based on the effective strain. Paper [Dagba, 1997] describes the numerical simulation of a tensile test of a hybrid composite using the LS-DYNA3D hydrocode. The material model employed in this simulation is based on Chang's theory (see papers [Chang, 1987a; Chang, 1987b]). The model was implemented as a DYNA-material database model (see a description of the model MAT_COMPOSITE_DAMAGE in the manual [LS-DYNA Manual, 1999]). In study [Dagba, 1997], the sample plate was V-notched and loaded quasi-statically and dynamically (at a given drop-weight velocity of approximately 20 m/s) in the instrumented tests. The loading direction was perpendicular to the free surfaces of the notch. The load-displacement curves were analysed and the paper [Dagba, 1997] claims that Chang's conventional theory cannot describe load attenuation after damage. Therefore, the theory was modified such that the elastic modulii related to the direction normal to the loading direction were set to zero and the Poisson coefficients in the direction of load were set to new effective values. The degradation rules remained unmodified in agreement with the basic theory.

Numerical investigation of the composite protection of helmets subject to high-velocity impact is reported in paper [Van Hoof, 1998], using the DYNA-hydrocode. This study exploited available experimental data on the ballistic limit velocity at penetration of woven aramid-phenolic resin laminates by Fragment Simulating Projectiles (FSP) where the ballistic limit velocity (V50) for a 5.6 mm calibre steel FSP of 1.1 g weight is nearly 600 m/s. The target was an aramid composite panel of 9.5 mm thickness (the target was composed of 19 layers, each of 0.5 mm thickness). The influence of damage accumulation on the numerical results of ballistic impact at an impact velocity of 600 m/s was analysed. The numerical simulation of target penetration was conducted with use of: i) an instantaneous fracture criterion; and ii) a damage accumulation fracture criterion. The numerical analysis found that the calculated V50 is lower than the experimental ballistic

limit velocity when using the instantaneous fracture criterion. The modelling described the V50 data more realistically with the damage accumulation criterion. Paper [Williams, 1999] describes the incorporation of a composite material model in the LS-DYNA3D hydrocode. An example of simulation of the load-displacement response of a notched composite sample is reported in this paper. The model employed in this study was based on anisotropic elasticity theory where the degradation of elasticity modulii with evolution of a damage parameter is controlled by two stages of damage: 1) matrix damage; and 2) fibre and matrix damage.

The damage accumulation fracture criterion has been considered in paper [Devries, 1997] for the case of dynamic loading of a composite. This study employed a homogenisation technique, but the composite material plies were simulated separately and they were stitched during computation at ply boundaries, which required large computational resources (parallelization during calculations was used in order to conduct this simulation). The model [Resnyansky, 1995a; Resnyansky, 1997a] (which was reviewed in subsection 4.2) was also developed with use of a homogenisation technique in order to simulate the transient response of composite materials. In addition, this model takes into account the micro-stresses in a composite induced by thermal and deformational processes. The kinetics for micro-stresses in unidirectional and laminated composites is associated with irreversible deformations in the composite constituents and with fibre rotation during the deformation (spin). This model has been implemented in the paper [Resnyansky, 2002c] as a user-defined subroutine for the DYNA hydrocode. The model has been used in this paper for the simulation of ballistic impact against carbon/epoxy composite targets and for simulation of plane wave propagation in a laminated composite [Borzilovsky, 1994; Resnyansky, 1997a].

Detailed descriptions of a number of approaches to damage modelling can be found in reviews (e.g., see [Lu, 1994; Rajendran, 1997]). Review [Lu, 1994] describes some theoretical tools employed for the penetration modelling of composite materials. The first part of the review outlines the anisotropic material theories, including elasticity, incremental theories, and visco-plasticity/elasticity. The second part lists failure criteria used with the theories. All the criteria listed in this paper are of a static nature. Stress components of the stress tensor in the local coordinate system (that is associated with the composite structure) are involved in the criteria and these criteria are considered in the form of a limiting surface in the stress space (the stress envelope). A special part of the review has been devoted to criteria based on linear fracture mechanics principles. These criteria link parameters in the energy release rates space (G_{I}, G_{II}, G_{III}), but this choice of variables does not change the static nature of the approach. Damage models have been described in the third part of the review and they are based on the principle of the degradation of elastic modulii when damage is evolving. Some theories, such as that described in paper [Matzenmiller, 1991], contain constitutive equations with a damage accumulation capability. This type of theory is of the Continuum Damage Mechanics (CDM) family. Subsections 4.2-4.4 outlined a number of examples of the incorporation of CDM models in hydrocodes. These subsections also reviewed a number of numerical

illustrations, using these models, which simulate dynamic (impact) problems for composite material targets.

7. After-impact evaluation and repair

7.1 Compression-After-Impact (CAI) test after LVI

Damage evaluation is not complete unless the after-impact response of a structure is known. The delamination or damage dimensions only give an idea of how dangerous the impact event is for the target. Qualitative assessment is obtained through a number of after-impact tests that can provide the residual characteristics (typically strengths) of the damaged sample. The behaviour of the damaged material depends very much on the loading conditions, so a number of tests should be conducted in order complement the after-impact evaluation. The part made from a composite material is generally just an element of structure. Therefore, it could be that the damage tolerance of the material embedded in the structure needs to be assessed. In fact, this situation is not unrealistic for parts where the design of the structure is a significant contributor to the factors affecting the tolerance. For example, the damage tolerance (the flexure stiffness against the number of impacts assessed in CAI tests) for a composite toecap was studied in paper [Lee, 2005]. The impact resistance was also assessed in this study, using an instrumented drop weight machine.

However, it is very hard to conduct evaluations for every part of a structure. Therefore, CSAI (Compressive Strength After Impact) as a property of the material (not a characteristic of the part assembly that involves the material embedded in a structure) is still the major parameter to be considered in damage tolerance studies. For example, paper [Dorey, 1974] considered the after-impact evaluation of carbon/epoxy laminates (CFRPs). Tests to determine the flexural and shear strengths were conducted with three-point bending, and tensile tests were also conducted with a servohydraulic testing machine.

It is widely accepted that the most critical characteristic of impacted composite skin of an aircraft is the response of the composite material to compressive loads. The reason for this opinion is that delamination is the most frequent damage mode in composite materials subject to impact. In its turn material delamination affects strongly the residual compressive strength. Another representative of After-Impact tests was reported in paper [Boccaccini, 2005]. A four-point bending test was used for the measurement of an elastic modulus (in fact, the after-impact stiffness was recorded and the modulus was calculated according to well-known beam flexure formulas). The maximum load approached in the test was also recorded. Both characteristics (the elastic modulus and the peak load) were in correlation with each other and could be used as after-impact characteristics along with CSAI. Another work [Kim, 1997] considered high velocity impact of ice particles (30-200 m/s) against composite targets. BVID (Barely Visible Impact Damage) is of primary interest in this study. The impact damage was assessed with four-point bending tests in

order to calculate the residual bending strength. The predictive methodology was based on the beam-bending model with pre-determined BVID or VID damage sizes. A wide variety of evaluation methods for composite materials have also been listed in a review by Abrate [Abrate, 1994] in the 'Experimental techniques' section.

The usual method for determination of residual compressive strength is the Compression After Impact (CAI) test. Compressive Strength After Impact (CSAI) is a measure of the damage tolerance of a material and may be used as a design characteristic to cover the BVID safety margin. Many studies conducted in the last decades, employ their own methods of CAI testing, but some recommendations exist as to how to conduct the test (e.g., see paper [Ilcewicz, 1989]). The paper [Ilcewicz, 1989] considered three typical NASA and aviation standards (experimental set-ups) used for the CAI testing: 1) coupons 10.2 x 15.2 cm with a thickness of approximately 4.5 mm have to be end-loaded in compression using an edge supported jig; 2) coupons 17.8 x 25.4 cm; and 3) coupons 17.8 x 30.5 cm with a thickness of approximately 6.4 mm for both standards (2 and 3), after impact the coupons have to be machined to 17.4 x 25.4 cm specimens and loaded as in the first standard. All of the standards use the recommended quasi-isotropic lay-up. According to another NASA recommendation (see [Standard-NASA, 1983]), 250 x 125 mm samples are to be clamped between two clampers with two 10mm-gaps at the bottom and the top of the rig. Two bar-shaped justifiers are to be used as the anti-buckling limiters. The open area is selected to be a rectangle. However, difficulties appear when the recommendations are applied to composite materials because of the variability of the materials in real-life situations. For example, paper [Liu, 1998] reported the crushing of edges of thin samples in the CAI test, which makes this standard almost unacceptable for thin 2-mm glass-epoxy cross-ply laminates.

CSAI is an important concept to evaluate the behaviour of a structure after impact. For example, fatigue that is a result of multiple repeatable quasi-static loads may lead to the failure of an impacted structure depending on the CSAI. The relationship between compression after impact and structure fatigue is not well studied. An example of such a study can be found in paper [Mitrovic, 1997], which describes approaches to the design of a damage tolerance criterion applicable to fatigue tests. The analysis demonstrated that the criterion is dependent on the load conditions in fatigue tests. Using the example of compression-compression load in a fatigue test after a 2-6J energy impact, it was shown that delamination growth is related to the level of the load in terms of the CAI strength. In particular, delamination did not occur at load levels less than half of the CAI strength. In general, the role of delamination is very important to the CSAI and has been considered in a number of publications.

Keeping in mind the exclusive role of delamination, it would be interesting to evaluate its influence on CSAI. Artificial delamination (5 cylindrical delaminations) introduced in a sample before a compression test was used in paper [Suemasu, 1997]. This study analysed in detail failure modes under compression testing. The compression tests and modelling of composite plates with multiple delaminations simulated a CAI test. Anti-buckling plates were separated from the sample by an air gap and the plates were greased in order to

reduce friction. A cross-direction displacement meter recorded the onset of buckling and failure for a number of delamination diameters. Finite-element modelling described the test results well and it was observed that at a large load (in the late stages of compression) the G_{III} component of the energy release rate dominated. It would be useful to study the influence of the number of delaminations on the results, but this issue was ignored in the paper.

As was mentioned, compression in the presence of delamination is the major cause of failure of structure integrity. As a result, delamination is considered to be the most important factor in reducing compressive strength after impact and the delamination size is frequently taken to be the only factor affecting the damage after impact. Many studies have attempted to determine the dependence of delamination size on CSAI and the impact energy. For example, the delamination size obtained with X-radiography was linked in paper [Choi, 1990] with impact energy (the energy range was approximately 0.2-0.7J) for impact with T300/Epoxy laminates. The existence of an Impact Damage Threshold starting at a certain impact energy level was claimed and this characteristic was declared to be a material parameter.

CAI analysis after a low velocity impact is reported in paper [Liu, 1998]. A drop-weight machine was used in impact tests for glass-epoxy cross-ply laminate composites. Two laminate thicknesses (nearly 2 and 6 mm) were considered. A number of 250 x 175 mm-samples were clamped to provide target dimensions of 125 x 125mm, 84 x 84 mm, and 42 x 42 mm. CAI testing was performed using the NASA recommended methodology (see [Standard-NASA, 1983]). The CAI test program included testing of impact damaged plates and plates with pre-made openings of the same size as those after impact in order to study the role of invisible delamination, which was present in the impacted samples and not in the pre-notched samples. The results showed that impact damage delamination is a major issue and the residual strength is much higher for pre-notched targets than for impact-damaged targets. The impact test program included testing of double and triple thin plate assemblies to study stiffness and delamination effects on absorbed energy. For the triple-system, it was observed that, for the same impact energy, the absorbed energy was higher than for a single thick system of the same thickness and that the peak force was lower. Using sensors that recorded force during impact, absorbed energy was evaluated and the paper showed that the absorbed energy achieves a maximum and remains constant after perforation. The results confirmed that the perforation threshold was achieved when the impact energy equalled the absorbed energy. The residual compressive force (which could be related to the residual strength) decreased and remained constant after the impact energy reached the level required for perforation. Residual compressive forces were similar for all in-plane target dimensions (for thick targets).

Usually, CAI tests record the load applied to the ends of a sample and CSAI is determined from load-displacement curves. For example, the CAI tests conducted in paper [Falzon, 1997] included compression of a sample between two blocks where the sample was restricted with a pair of anti-buckling plates that had a 4 cm-diameter opening for the damage area. The CAI strength limit was defined as a maximum stress achieved before a

load drop. CAI tests are laborious and expensive, so a simpler approach to the evaluation of damage tolerance was suggested in paper [Feraboli, 2004]. Quasi-isotropic laminates were tested with a drop-weight machine. The contact duration was assessed in three consecutive tests: the first and third tests were used for duration assessment (elastic impact tests) and the second test was the main test to produce damage in the composite sample. The impactor energies after impact (the energies at rebound) were not identical in the first and third tests if the sample was damaged in the second test. The ratio of respective rebound energies was analysed in this study, allowing the authors to define three regimes: i) subcritical, where the rebound energy of the drop weight after impact (i.e., in the third test) is equal to the energy of the impactor for the undamaged sample (thus, the energy ratio is nearly 1); ii) 1st supercritical. The energy ratio is nearly constant, when impact energy increases, but is less than 1 (the sample has matrix damage and/or delamination); and iii) 2nd supercritical where the energy ratio is noticeably reduced with increasing impact energy. In this case fibre breakage has occurred in the sample. In this study, the contact duration was associated with laminate stiffness. Concluding, available CAI and tensile after impact (TAI) evaluations lead the authors to propose this simplified three-test methodology for evaluation of damage tolerance.

The influence of manufacturing on composite properties and damage resistance is significant and was reviewed in subsections 5.5 and 6.6. Impact resistance to low-velocity impact and damage tolerance to impact are also sensitive to manufacturing processes. CAI testing after a 2-8 J impact is described in paper [Ishikawa, 1997] where a number of strain gauges were placed on samples, allowing differences in strain to be observed at various locations with respect to the impact point. Variation in delamination resistance due to manufacturing processes (manufacturing with and without an autoclave) was reported.

The influence of parameters of the Resin Transfer Moulding manufacturing process on the CAI strength of composite samples was discussed in paper [Berthet, 1997a], where samples were subject to drop-weight tests with energy levels of 5-35J. Manufacturing processes may also influence interlaminar shear stresses as was shown in paper [Berthet, 1997b]. In addition to the composite type, the CSAI can also be influenced by the composite structure. An example of the influence of stitching on CAI strength was reported in paper [Qi, 1997]. The influence of ply orientations on CAI strength was noted in paper [Puhui, 1997]. In this study, CAI tests were conducted using a compression test machine with the compression of a sample between two steel plates separated from the sample by Teflon spacers. The samples were subject to low-velocity impact with energy levels from 14 to 58 J (using a drop weight). The influence of the target in-plane elastic modulii on CAI strength was noted. In paper [Susuki, 1997], 2D and 3D Carbon/BMI resin composites were tested. The composites were manufactured, tensile tested, C-scan inspected, subjected to a low velocity impact, and CAI tested. During the CAI testing, 4 gauges were placed on the samples and stress-strain curves were recorded. The authors claim an improved CAI performance for the 3D-composite. For the 3D-composites, the CAI tests recorded smaller stress at a given strain, apparently due to the stress relaxation in the stitching locations.

Paper [Han, 2000] reported on studies of glass/aluminium composites of two types. Room Temperature Composite (RTC) was fabricated from alternating layers of aluminium and glass joined by epoxy at room temperature. High Temperature Composite (HTC) was joined by epoxy at high temperature and this manufacturing process generated significant interlayer micro-stresses when the composite was being cured. An FEM assessment showed micro-stress levels of up to 40 MPa. Static and dynamic (low velocity impact) tests revealed that micro-stresses reduce fracture failure under static and LVI loads. The benefits of micro-stresses diminish when the sample is impacted at velocities corresponding to partial or full penetration.

Low-energy impact is associated with slow mechanisms of damage accumulation. This is why environmental factors might need to be considered when assessing the damage tolerance of composites to this level of impact. Paper [Komai, 1997] reports on three composite materials after low velocity (drop weight) impact at energy levels of 1-8J. The influence of water absorption on the delamination area after impact (which was inspected with a scanning acoustic microscope) and CAI strength were determined for these composites. A Carbon Fibre (CF) reinforced composite with a thermoplastic matrix (AS-4/PEEK) had higher damage tolerance than carbon fibre and aramid fibre reinforced composites with an epoxy matrix.

CAI tests for carbon/epoxy targets subject to LVI (see paper [Dost, 1991]), using the set-up and lay-ups described in subsection 5.5, showed that the effect of the stacking sequence on CSAI diminishes as the impact energy increases. Generally, the more homogeneous the ply orientation variation in the through-thickness direction the more symmetrical the damage and the more homogeneous the distribution of 30° or 45° sector delamination wedges (depending on the lay-up). These delamination wedges spiral down to the distal side of the target. The homogeneous 30° ply lay-up distribution, when resulting in symmetrical and homogeneous through-thickness damage, resulted in highest CSAI achieved. Larger ply group thickness resulted in a larger delamination area and in a higher CSAI in a given sublaminate. However, an increase of the ply group thickness resulted in a decrease of CSAI, because an increased planar delamination provoked premature buckling during the CAI test. The 45° ply lay-up distribution with maximal ply group thickness (3 plies with the same orientation for 4 groups of the 12 ply laminate composing half of target thickness) resulted in the highest asymmetry of damage. The minimal damage area was at sublaminates that are close to the target face and maximal damage was achieved at the centred plies of the target. This stacking sequence provided the lowest impact tolerance for the material.

The testing of weft-knitted glass textile composites is described in paper [Khondker, 2005] for different patterns of knit. 3 mm thickness samples were impacted using a drop-weight testing machine (the drop weight impact energy varied from 1.7 to 27.3 J) and the samples were CAI tested with an instrumented rig which had anti-buckling plates with 40 mm openings to accommodate the impact damage zone. Damage after impact was assessed by visual inspection using transmitted light. Damage resistance was evaluated as the dependence of the damage area on the impact energy. Damage tolerance was evaluated as

the dependence of the CSAI (normalised by the original compression strength) on the impact energy. During the CAI tests, a loading was performed in the wale direction (the stitching direction of the textile sample) and damage propagated in a direction perpendicular to the loading direction. The test results were compared with data available for unidirectional prepreg tape, fabric and braid composites. The damage resistance, which has been characterised by the damage area in this study, manifested as a highly localised damage (nearly the tup diameter) for weft-knitted structures. A comparison of test results for different composite structures showed that damage resistance and tolerance were highest for weft-knitted structures and the best performing structure had the smallest weft-knit loop (the highest loop density). However, as was admitted by the authors, in-plane mechanical performance of weft-knitted composites is reduced as a trade-off for high impact performance.

Paper [Qi, 1997] analysed the influence of composite material moisture absorption on CAI strength. The CAI tests in this analysis were performed with a testing facility with buckling plates that had a 4 cm diameter opening accommodating the damage zone. The LVI damage zone was produced by impact energies up to 6 J. A slight effect of the moisture content and hygrothermal cycling before and after the impact on CAI strength was reported in this study. Paper [Bibo, 1997] described CAI testing results for two composite materials (carbon/epoxy and glass/epoxy laminates). The composites were studied for transonic airpcraft applications, so the impact and compression tests were conducted at elevated temperatures (up to 150° C). The samples were C-scanned after impact and the damage size and CAI strength were documented against the impact energy (up to 10 J). The testing of hygrothermal effects included a study of the effects of moisture content on CAI strength. This study concluded that the idea that the residual strength is mainly controlled by the impact energy might be misleading. Certain composites may have a significant environmental conditioning influence on the CAI strength.

The purpose of paper [Bull, 2004] was the validation of an equivalent-hole analytical technique for the CAI evaluation of sandwich panels. In general, the idea of replacing a much more complex analysis of a sample with damage and internal delamination due to impact by the simpler analysis for pre-notched samples attracts the attention of many researchers. Therefore, the compressive behaviour of a composite sample with a pre-made hole is a well studied area of material characterisation. It should be noted however, that many aspects of the compressive behaviour of pre-notched samples are yet to be resolved. For instance, a recent experimental and numerical study (see [Saha, 2004]) of the compressive strength for sandwich samples demonstrates some of the difficulties. Tracing the damage propagation during CAI tests is not a simple task for sandwich panels, so digital speckle photography and strain gauges at different locations were used in this paper [Saha, 2004] to observe the onset of fracture. The materials tested were a sandwich material with a 60 mm PVC core covered by 1.8 mm thickness quasi-isotropic CFRP face sheets, and a sandwich material with a 50 mm core covered by 5.4 mm thickness face sheets. For validation purpose, small panels (150 x 150 mm) with pre-made 30 mm holes and 30 mm cracks (a notch that was oriented perpendicular to the loading direction) were tested under compression as well. Larger panels (300 x 300 mm) were subject to LVI with

impact energies of 30, 50, 100, and 250 J, using the hemi-spherical and pyramid-nosed tups. The damage zones after impact were evaluated by C-scanning. This evaluation is used in order to determine an equivalent hole, when predicting the CSAI with the equivalent-hole technique (this technique was reported in paper [Soutis, 1991] and will be reviewed below in subsection 7.4). The conclusion of the paper [Saha, 2004] was that the equivalent-hole technique describes the CSAI results reasonably well. However, the technique does not segregate the theoretical CSAI results between thin and thick face sheets (for panels with the pre-made holes and notches). The prediction accuracy is within 6% for damage induced by the hemi-spherical impactor and within 15% for the pyramidal-impactor. The predictions are less accurate for the 60 mm core samples than for the 50 mm core sandwich panels.

Low velocity impact damage of the order of BVID (BVID is defined as 1 mm indentation) has been performed in paper [Cvitkovich, 1998] with a drop weight tower onto sandwich panels that are commonly used in helicopters such as RAH-66 Comanche. A Nomex core sandwiched between carbon/epoxy face sheets was tested with 2, 3, and 4 layers of face sheets. An aluminium honeycomb core was also used for the 4-face-sheet configuration. The samples were CAI tested and damage mechanisms during the testing were studied with 4 strain gauges mounted on the face sheet surface in the vicinity of the expected damage. The Moiré imaging technique was used for tracing the onset of a failure. When comparing the aluminium-core and Nomex-core sandwich materials during CAI testing, it was observed that the strain was almost constant prior to failure for the aluminium-core material, but a significant variation of strains was recorded during the testing of the Nomex-core material. Thus, the study [Cvitkovich, 1998] concluded that core stiffness is a critical parameter for describing the failure mechanism during CAI testing.

7.2 The influence of preload and interleafing on CAI

The effects of preload before impact on CAI results would be of great interest for real-life situations (the influence of preload on the impact resistance was addressed in subsection 5.3). Paper [Zhang, 1999] describes an analytical FE method and results of CAI testing for carbon/epoxy composite samples with quasi-isotropic lay-up. The samples (the in-plane dimension of the samples was 20 x 25 cm and sample thicknesses were of 2 and 4.3 mm) were subjected to low-velocity impact with impact energy in the range of 10-30J. The samples were compressively preloaded, impacted, C-scanned, and CAI tested. For thin 2 mm samples, the preload could not be very large because of the threat of buckling. For all samples CSAI increased with preload. For thicker 4 mm samples the preload could be significant (the preload could be up to 1.2 times the initial buckling load). In the case of low-energy 10 J impact the preload was beneficial to damage tolerance resulting in a smaller delamination area and a higher CSAI, when compared with unloaded samples. At an intermediate level of impact energy (20 J), a small preload can still be beneficial to CSAI. However, for large preloads the sample failed under impact. At the highest level of impact energy (30 J), the delamination area increased and the CSAI decreased when the preload increased.

The tensile testing of composite samples after ballistic impact is described in the report [Olster, 1972]. Graphite/epoxy and boron/epoxy targets were pre-tensed before impact (usually up to the pre-stress levels of 30 and 70% of the ultimate tensile strength σ_u). The impact conditions for these tests were outlined earlier in subsection 6.6. This study showed that the tensile strength after impact (σ_t) varied from 52 to 65% of σ_u for the boron/epoxy targets and from 62 to 73% of σ_u for the graphite/epoxy targets. Only slight variations of σ_t were observed when the impact velocity, projectile calibre, or pre-load was varied. The major reason for the σ_t variation was the material lay-up. In preliminary studies it was also shown that the value of σ_t for impact-damaged samples was almost identical to the tensile strength of samples with pre-drilled holes. It follows from these test results, that tensile tests after impact are not very sensitive to delamination and to internal damage in the matrix. A difference in the damage state is the major difference in the states of the impacted and pre-drilled samples. In contrast to the tensile tests, these factors are of crucial importance for the compression tests.

Embedding intermediate layers (interleaving) in a material structure, which will result in the relaxation of micro-stresses, is a method for increasing damage resistance and damage tolerance (the CAI strength) in composites. Paper [Masters, 1989] explains that interlaminar shear and normal stresses at the micro-structural level could easily be introduced during manufacture. Damage in such composite materials usually starts at a free edge, notch hole, ply drop, bonded or bolted joint, where the micro-stresses due to manufacturing (e.g., when thermosetting) promote the damage. Micro-stresses can also initiate delamination during impact. The paper [Masters, 1989] studied interleaving effects (structure modification by inserting a resin layer with specified properties between laminates during the manufacture of the composite) in order to reduce interlaminar micro-stresses. The residual strength of graphite/epoxy composite samples subjected to drop-weight impact was measured for 10 x 15 cm samples (the sample thickness varied from 1 to 1.5 mm). CAI testing results demonstrated 20 to 50% increase in the residual strength, depending on the composite structure and method of manufacturing. The major absorption mechanism during impact is observed to be transverse cracking and this type of damage was significantly reduced, when compared with the baseline material without interleaving. Tests associated with the energy release rate demonstrated that the most suitable parameter for characterising the impact resistance associated with the CSAI, could be the shear mode energy release rate (G_{II}).

The concept of interleaving during laminate manufacture can be used for improving impact resistance. Paper [Yi, 2003] suggests the interleaving of carbon laminates with thermoplastic thin 10 μm films, resulting in a periodic structure as an alternative to toughened resin and traditional interleaving. CAI tests demonstrated an increase in damage resistance for the samples manufactured with the suggested technology, when compared with the samples manufactured with use of the toughened resin and traditional interleaving (ten 10 μm films at the middle of the composite material). This damage resistance advancement was explained by the periodicity of the structure (the corporate effect) and a reactive-generated substructure during the manufacture of the laminates.

The influence of moisture content on impact resistance and damage tolerance of composites with interleaving is considered in paper [Imielińska, 2004]. The composites studied in this work were an aramid-glass-fibre hybrid fabric and a material consisting of aramid-fibre fabric with glass-fibre interlayers. These samples were subject to LVI followed by the CAI testing. The strength retention factor (the residual strength over the compressive strength of an undamaged sample) was determined for impact energies E_i in the range from 0 to 32 J. A CSAI prediction was attempted with the Caprino's model (see [Caprino, 1984] and the model review in subsection 7.4), using the C-scanning results for damage evaluation. The tests and predictions showed that the water-saturated samples were less sensitive to impact, exhibiting the highest damage tolerance with the interlayer 'wet' sample (0.77 is the retention factor at the maximum energy E_i = 32 J). For the 'dry' fabric this retention factor reached 0.63 at the maximum impact energy E_i. It should be noted that the model gives a higher damage tolerance (at the high E_i) for the hybrid 'wet' samples when compared to the 'dry' samples, which is in agreement with the tests down to moderate values of E_i.

7.3 CAI testing of ballistically damaged targets

The papers considered in previous subsections illustrate the general tendency of composite materials to exhibit gradually decreasing damage tolerance as impact energy increases from a low value. Along with this, damage increases from the impact point, involving an increasing number of composite laminates. However, with higher impact velocities the damage becomes more localised, so the damage tolerance does not decrease with an increase of impact velocity beyond a critical limit. An investigation of the damage tolerance of composite samples subject to ballistic impact is reported in paper [Boccaccini, 2005]. The elastic modulii of damaged samples and the maximum load before the failure, assessed during three-point bending tests, were used as measures of damage tolerance. A range of ballistic impact velocities was used, including the ballistic limit velocity (V50). The study [Boccaccini, 2005] confirmed the existence of a zone of maximum damage where ballistic tolerance is minimised. The ballistic tests described in this paper were conducted with glass projectiles, which might be subject to a deformation and fracture during impact. The composite type and the method of determination of ballistic tolerance could be an issue as well. However, the existence of such a minimum is important because it indicates the point where the energy absorbed by a target is maximised.

The traditional way of assessing strength after impact is by evaluation of the delamination and damage areas. Visible damage and damage which affects the results of CAI testing (for example, the delamination area assessed by C-scanning), can differ significantly for a ballistically damaged composite target. This difference should be taken seriously, keeping in mind the relatively small and localised visible damage in composites, observed after ballistic impact. For example, C-scanning inspection results were reported in paper [Wang, 2004b] for quasi-isotropic carbon/epoxy composite targets tested under ballistic impact conditions in [Resnyansky, 2002c; Resnyansky, 2004c]. The paper [Wang, 2004b] reported the ratio of the damage area (evaluated with C-scanning) to visible damage for test conditions [Resnyansky, 2004c] which included obliquity angle, impact velocity and

thickness of the target. This damage ratio changed from a value of 2-3 for frontal and distal surfaces of targets for oblique impact, to a value of 5-6 for frontal surface and 3-4 for distal surface of targets for normal impact at relatively low velocities of impact (the ratio decreased with the impact velocity and slightly increased with the target thickness).

Damage tolerance studies for composites subject to high-velocity impacts (including the whole range of CAI testing) have been widely studied in the past few decades. Most approaches deal with damage assessment using basic C-scanning. For example, for the hypervelocity impact of graphite/PEEK composite plates considered in paper [Tennyson, 1997] it was found that the damage area was approximately 20% larger than the entry crater area. The damage area in this study was related to the delamination area obtained with C-scan inspection. The damage and delamination areas were found to be proportional to the cubic root of the projectile's kinetic energy and target thickness and inversely proportional to the projectile diameter. Paper [Ayax, 1991] considered high-velocity impact (up to 500 m/s) by a cylindrical steel projectile against fibre-glass laminates. The target thicknesses varied from 8 to 12 mm and the thickness was selected so that the projectile was stopped by the target (therefore, all of the impact energy was absorbed). The absorbed energy was calculated from the area of delamination, which was assumed to be conical in shape (the base of the cone was determined by the rear-side delamination area, the so called whitening zone). The energy was found to be proportional to the depth of penetration (the depth where fibres were broken by the projectile). It should be noted that a cone-shaped area of delamination is quite a crude approximation to the actual damage zone. An attempt to study the polymer composites for body armour is reported in paper [Cunniff, 1989]. The role of structure factors such as the properties of yarn/fibre and weave geometry were considered from the viewpoint of their effects on ballistic performance.

The widely used delamination area may provide only a limited indication of after-impact properties, so more precise tests for samples subject to impact may be needed. Moreover, the loading conditions under which the impacted structure will operate may need to be included in test set-up via testing at specified load modes. References are readily available for a variety of after-impact tests. For example, paper [Dorey, 1974] considered carbon/epoxy laminates (CFRP) with thicknesses of 1.5 and 3 mm subject to drop-weight impact and to high-velocity impact (the impact velocity was up to 300 m/s) by steel 6 mm diameter balls. The samples had 15 x 15 cm in-plane dimensions and were simply supported. After impact they were C-scan inspected and tested for residual flexural strength, residual shear strength, or residual tensile strength. The flexural and shear strength tests were conducted with three-point bending and the tensile tests were conducted on a servohydraulic testing machine. In this study, for thin laminates the residual flexural strength dropped almost to zero for impact energies of 2-3 J. At higher impact energies (corresponding to impact velocities greater than 80 m/s), the strength increased to values corresponding to the strength for plates with a prefabricated hole. For thick targets, the flexural strength decreased nearly monotonically with impact energy. The tensile strength dependence was found to be similar, but the strength did not drop to zero. The shear strength also decreased monotonically and it correlated well with the

increase in the delamination area. The most damaging range of impact velocities in this study was found to be from 60 to 80 m/s.

Because of the high sensitivity of pre-impacted composite plates to compression, CAI tests are believed to be the most relevant to the study of structure survivability. Detailed studies of composite response after impact may involve a variety of direct CAI tests. A relatively simple approach has been demonstrated in paper [Da Silva Junior, 2004]. GFRP panels were subject to impact by a large calibre hand-weapon projectile with an impact velocity of 328 m/s, which resulted in a large delamination spread. After impact the panel was cross-sectioned into a number of smaller samples that were classified by the delamination extent. The delamination damage was assessed with the use of a flatbed scanner as described in the paper [Nunes, 2004] (this technique was reviewed in subsection 6.1). After-impact tests evaluated the residual stiffness using a tensile testing machine and a non-instrumented Charpy test set-up with a pendulum. The position of the pendulum before and after impact was used to measure the residual fracture energy (actually, the absorbed energy). This study observed that the stiffness was almost unaffected by the presence of delamination (except for samples from the direct hit area). However, the residual energy remained almost constant until the delamination spread over 50% of the sample area after which it rapidly reduced to about 1/10 of its original value.

Report [Fink, 2001] describes the damage tolerance of glass/epoxy laminates. Ballistic impact with a velocity of impact slightly below V50 was believed to produce maximum damage to a composite target and this velocity was selected to be the baseline velocity in these tests. C-scanning with three levels of scanning depth (10%, 50% and 80% below the impact surface) were employed. Composite materials with two types of glass fibres and three types of resin matrix were manufactured using RTM (Resin Transfer Moulding). Plain composite structures and structures with several densities of through-the-thickness stitching were tested. It was found that stitching resulted in a reduced damage diameter (by 18% on average) after ballistic impact. G_{IC}, which was determined through DCB (Double Cantilever Beam) tests, was significantly larger than for the plain composites, but no increase in the CSAI was observed for the stitched samples. CAI failure modes were considered both theoretically and experimentally. It was observed that the predominant failure mode during CAI tests was unstable delamination growth, so increasing G_{IC} would reduce the growth. However, the G_{IC} increase due to the stitching did not result in an improvement of the CSAI. In this case, the in-plane failure mode that is independent of fracture toughness was the reason for the panel failure. While the stitching improves multi-impact performance via a reduction in the damage size, it may also increase fibre damage. Stitching also causes a shift of the failure mode from delamination growth to in-plane failure. As a result of this study, the report has concluded that material design optimisation is necessary in every individual case.

CAI testing of S2 Glass fibre composites with three types of matrices (polyester, vinylester, and epoxy) is described in paper [Gillespie Jr., 2003]. Fragment-simulating 12.7 mm projectiles with a pre-selected impact energy (465 m/s velocity of impact) were used in all tests. The delamination damage was assessed by C-scanning inspection at three depths in

the through-thickness direction (10% from the impact surface of the target, the centre of the target, and approximately 80% from the target surface). The composite samples were instrumented with strain gauges in order to trace buckling during the CAI tests. Two series of tests at a higher impact energy were conducted in this study for glass/vinylester and glass/epoxy samples with ceramic tiles attached at the impact side (appliqué armour). Stitched and unstitched samples were also tested for comparison. The results showed that stitching reduced the damage region, but the delamination area was not substantially reduced and, as a result, the CSAI increase was quite small. For tiled samples, stitching reduced the damage and resulted in a slight increase of the CSAI. Predictions that were made with the point stress concentration criterion (see [Whitney, 1974]) were reasonably accurate, but non-conservative due to possible stress relaxation caused by matrix cracking that cannot be traced by C-scanning inspection (in contrast to the observations of delamination).

Paper [Suarez, 1975] reports on residual after-impact properties of boron/epoxy laminates. The composite targets were subjected to ballistic impact with full and half loads of standard AP 7.62 and 12.7 mm munitions. The impactors were AP projectiles and AP incendiary (API) 23 mm ammunition. The target area was 15 x 15 cm of a 15 x 30 cm composite panel. The material structures were: i) E-laminates with 4 filament orientations (the quasi-isotropic lay-up) with a thickness of 1 mm; and ii) ZZ-laminates with 3 filament orientations and a thickness of 1.5 mm. These samples were impacted in free-stress and pre-loaded states (up to 60% pre-tension of the limit load) at obliquity angles of 0, 30, and 60 degrees. A series of 27 tests (with 3 undamaged specimens for a control) were conducted. Visual and X-ray inspection indicated a maximum 5 cm delamination spread from each side of the penetration hole in several cases. Residual tension strengths for the E-laminates impacted by AP projectiles were found to be insensitive to the obliquity angle and to the projectile velocity. The strength reduction was approximately 12% when compared with the strength of controlled undamaged samples and 6% compared with the strength of non-impacted samples that have a predrilled hole of the projectile diameter. The residual tensile strength was even more insensitive to the obliquity angle and the impact velocity for API rounds. The residual strength was observed to be responsive only to the projectile diameter. After-impact fatigue testing showed a reduction in the residual tensile strength of the order of 5% for E-laminate samples (after a fatigue equivalent to 16000 flight hours). Six E-laminate samples were damaged by impact with 12.7 mm projectiles and then subjected to CAI testing. The samples that were pre-loaded before impact had lower CSAI (by 11%), when compared with the undamaged specimens and the CSAI of samples that were free of stress before impact was reduced by 7%. Six sandwich specimens, composed of a honeycomb aluminium core and composite face-sheets, were impacted by 12.7 mm AP and API rounds. In this case, the residual CSAI was found to be very sensitive to the projectile calibre and the obliquity angle. Comparisons of the residual strengths for the composite targets with the residual strengths for targets made of aluminium (Al) and titanium (Ti) alloys demonstrated that the composite damage tolerance was comparable to those of Al and Ti targets of the same thickness. This observation held true even for the adverse testing condition of an impact velocity of nearly 200-400 m/s and an obliquity angle of 60°. High pre-loads and low impact velocities

resulted in the in-situ fracture of the ZZ-laminate samples. Nevertheless, the damage tolerance of the composite targets is believed to be generally no worse than the tolerance of the Aluminium targets. Fracture did not occur for the E-laminate samples, so filament orientation effects associated with the composite structure may be significant. The ballistic tolerance results demonstrated that composite targets could have significant performance/weight advantages over metallic targets. However, due to the limited number of tests, the residual strength-impact velocity curves for the composite targets do not really cover the same impact velocity and angle ranges as the curves for Al and Ti alloy targets, so these conclusions should be verified in further testing.

A study (see [Christopherson, 2005]) on the ballistic resistance of sandwich samples composed of foam-filled honeycomb core and two and one side laminate face sheets has been reviewed in subsection 6.6. After impact these samples were also tested using CAI set-up. A constraint fixture was used in order to prevent the samples from buckling, except in the localised damage area due to impact. In all of the CAI tests the following sequence of failure modes was observed: i) local buckling due to interface delamination in the area of impact localization, ii) followed by crack propagation in the face-sheets, and iii) shearing of the foam core. According to this study, the CSAI reached a maximum at the critical impact energy, where energy absorption also approached a maximum. At this extreme, the damage was minimal (the damage increased with increasing impact energy). The local bulking observed during the CAI tests was minimal too and it was highly localised.

7.4 CAI modelling

The residual material response under tension is usually easy to predict and it is related directly to the size of the damage hole if available. The tensile response is predictable because it is mainly determined by the unbroken fibres of the composite material.

Paper [Husman, 1975] suggested an analytical assessment of the residual tensile strength s_R of composite laminates in the following form

$$s_R = s_0\,(W - K \cdot W_k\,/W)^{0.5} \quad ,$$

where s_0 is the static tensile strength of an undamaged specimen, W is the specific (with respect to the target thickness) volumetric work required to break the undamaged specimen, W_k is the specific kinetic energy of the impactor, and K is an empirical constant. An analogy with a circular flaw inserted in a coupon tested under tension was used in order to derive the formula. The fitting parameter K was found to be primarily affected by the specimen's width (not by its thickness). The tests were conducted for beam composite targets. The target beams were made of 0/90 laminates, the beam widths varied from 12 to 25 mm and the beam thicknesses were 2.5 and 3 mm. The targets were impacted by spherical steel projectiles (the projectile diameter D was 3.5 and 6 mm) with impact velocities from 40 to 300 m/s. Tests of a variety of composites demonstrated the validity of

the formula for impact velocities less than V50. For higher velocities, the residual strength was found to be equal to the static strength of the coupon with a hole diameter of *D*.

Assessment of the compressive strength is not straightforward because non-visible delaminations significantly reduce this strength due to buckling. Therefore, it should be noted that failure mechanism for compressive testing of impact-damaged samples may differ from the failure mechanism for predrilled-hole samples, especially in the case of sandwich materials. For example, sandwich samples with a Nomex core and carbon/epoxy face sheets have been considered in paper [Cvitkovich, 1998]. These samples, which were subject to LVI, were tested using CAI facilities. Strain recordings for a sample equipped with strain gauges in the vicinity of the LVI-damage zone, and recordings for a notched sample (with pre-made hole) have been compared using CAI testing [Cvitkovich, 1998]. The comparison showed that the strain changed insignificantly for the notched sample and it varied within a wide range for the impact-damaged sample. Thus, the transfer of the CAI results from pre-notched to damaged samples should be viewed with caution.

Nevertheless, the use of an equivalent hole can be used to predict composite failure, but the prediction method should employ a hole size that is assessed, for instance, from a C-scan image of a damaged sample (see [Soutis, 1991]). The model developed in paper [Soutis, 1991] assumed that the failure stress for a notched sample is identical to the stress that initiates crack propagation (the hole is considered to be a large crack). The compressive strength of an un-notched sample and the fracture toughness G_c were needed for a prediction to be made. The paper [Soutis, 1991] noted that the model fails to predict damage growth in the initial stage of fracture because of the linear fracture mechanics assumptions. The results of this prediction could be linked with compressive strength after impact as suggested in paper [Soutis, 1996]. An analysis of a number of the samples subjected to LVI allowed the authors to conclude that the circular shape of a typical damage zone may be used as the shape of an equivalent hole for model assessment. X-ray, C-scan and de-ply studies (each ply was peeled away and SEM-inspected) summarised in the paper [Soutis, 1996] showed that delamination, crack damage and fibre breakage are all of a roughly circular shape. It was also noted in this paper that the model effectively predicts CSAI for composites where the majority of plies are primarily aligned with the loading direction (for example, not too many 45° cross plies).

A simple model (sometimes referred to as the Caprino's model described at first in the paper [Caprino, 1984]), which links the strength σ_R (this model evaluates the strength regardless the loading mode – either tensile or compressive) with the impact energy E_i by power law, is frequently used for evaluation of the residual strength:

$$\sigma_R = \sigma_0 \, (E_{th}/E_i)^n \; , \tag{7}$$

here σ_0 is the tensile strength of the undamaged material, and E_{th} is a threshold energy. When the impact energy is lower than the threshold energy, the residual strength is equal to σ_0. The model (7) was validated in the paper [Caprino, 1984] for graphite/ epoxy

composites subject to low energy impact. Data collected in paper [Kang, 2004] for carbon/epoxy laminates subjected to impact energies from 1 to 6J (the mass of the impactor, launched by a gas gun, was nearly 60 g) were also in agreement with (7). Using the assumption of a power law relationship between the impact energy E_i and the damage area c, the formula (7) can be rewritten in the following form:

$\sigma_R = \sigma_0 \, (c_{th}/c)^m$,

here c_{th} is the limiting damage size at which the residual strength starts to be affected. This model (7) was used in paper [Imielińska, 2004] for the CSAI evaluation of 'dry' and water-saturated composites.

Analytical assessments usually ignore many of the issues (mentioned above), which are associated with the damage mechanisms of composites under compression. The semi-empirical formulas deal with a simple assessment of the damage zone from a C-scan image, and they employ the damage size as an input for the theoretical method, along with a number of fitting parameters. For example, paper [Falzon, 1997] reports on the CAI strength for 2D braided carbon/epoxy composites. Experiments in this work involved low-velocity drop-weight impact (up to 14J) of composite targets. The impact tests were followed by a C-scan inspection of the samples and concluded with a CAI test. The C-scan inspection showed that the damage was mainly due to delamination. The theoretical assessments conducted in the paper [Falzon, 1997] were based on the delamination area approximated as an elliptical zone (which was obtained with the C-scan). This elliptic zone was used in two analytical solutions employing an open-hole technique, in which the hole is an elliptical opening (comparable to the elliptic damage zone). Each of the two solutions used one fitting parameter (a characteristic length).

Paper [Avery, 1989] analysed the residual strength (CSAI) of a carbon/resin quasi-isotropic laminate. An analytical method was developed using anisotropic elasticity theory. A characteristic damage size (CDS) zone was represented as an elliptical delamination/fracture zone and this zone size was assessed from C-scan data. This zone (the CDS) was used in the analytical solution that was obtained for an elliptical inclusion where it was assumed that the inclusion has a properly selected degraded elastic modulus. This solution was found to be an upper bound to another available solution and experiment. The CDS can be directly evaluated with FE modelling. A successful example of a delamination prediction of carbon/epoxy laminates subject to ballistic impact was demonstrated in the paper [Wang, 2004b]. The prediction was based on a solution with DYNA code and followed by validation with C-scanning results. A finite element stability analysis was conducted in the paper [Dost, 1991] that was reviewed in detail in the previous sections. Numerical results from modelling of the compression testing of a composite matched well with CAI test results.

FEM analysis with the ABAQUS software has been conducted for simulation of the compression of composite laminates with an open hole [Wang, 2004a]. Comparison of the numerical results with experiments shows that a progressive damage model for a

composite laminate may accurately describe an open-hole problem that is suitable for CAI assessment. Linear analysis was also suggested in this paper as a way to solve this problem provided that an appropriate secant modulus is fitted by a calibration from one test. FEM analysis was used in paper [Gillespie Jr., 2003] along with the point stress concentration criterion (see [Whitney, 1974]) in order to determine an effective stiffness of the inclusion that represents the damage area. For that purpose, a number of simulations were conducted with a parameter responsible for stiffness reduction. A calibration experiment was conducted on the compression of a single damaged sample with strain gauges placed both at a remote area (with regard to the damaged zone) of the sample and at the edge of the damaged zone. A 75% loss of stiffness was evaluated from the experiment [Gillespie Jr., 2003]. Elastic parameters employed in the FEM code were used for determination of the stress concentration factor from well-known formulas on the compression of infinite plates with a circular inclusion. The stress concentration factor was used in the modelling described in the paper [Gillespie Jr., 2003] in order to predict CSAI for the remaining samples.

An analytic CAI evaluation method has been developed (see paper [Ilcewicz, 1989]) using an inclusion with reduced stiffness for modelling the CDS zone. This study considered CAI tests and the influence of sample width, ply group thickness, and stacking sequence on the CSAI and verified the method by experiment. Paper [Davidson, 1989] suggested another analytical method based on a reduced stiffness approach for the CDS zone. This zone was supposed to be an elliptically shaped delamination, which may be multiple in a given interlayer location. The point stress concentration criterion was proposed in paper [Whitney, 1974] for a composite material. An analytical solution was considered for the in-plane compressive behaviour of an anisotropic elastic plate with an inclusion that presumably replaces the CDS zone. The material properties of the inclusion have degraded elastic characteristics from those of the original composite. Normally, due to stress concentration at an inclusion edge, the stresses in the vicinity of the zone are exceedingly high (the stress concentration is regulated by the stress concentration factor, which is the ratio of stress at the edge of the inclusion to the stress in the remote area of the sample). In order to avoid singuliarities when using the point stress concentration criterion [Whitney, 1974], a comparison was made between the strength of undamaged material with stress taken at some distance from the inclusion edge as a criterion. Using this criterion, a formula was proposed in paper [Gillespie Jr., 2003], according to which the CSAI is the ratio of the strength of the original material to the stress concentration factor and this factor was related to residual stiffness loss. A more general expert system has been designed as a computer program RESTRAN and described in report [Saether, 2001]. The program combines structural analysis with prescribed properties of composite parts. This software uses elastic and fracture properties of composites and makes use of a geometrical analysis of the cross-influence of parts involved in the analysis. The analysis generates an assessment of the residual strength characteristics of structures, within a nominated safety margin.

The traditional circular hole that is usually used for CAI modelling has been re-examined in paper [Puhui, 2002] and the determining role of the damage width was declared. An

elliptic hole was adopted in this study with the long axis of the ellipse directed perpendicular to the loading axis for CAI testing. The length of the ellipse was chosen to be equal to the size (width) of the damage zone obtained from C-scan inspection or X-ray photography and the width of the ellipse was selected to be the indentation dimension (in the case of penetration the projectile diameter was accepted as the indentor size). The substantiation of the hole shape was based on an analysis of the failure mechanism under compressive testing of a composite. A lay-up independent failure criterion (the Load-Bearing Ply Failure (LBPF) criterion), which was employed earlier for the compressive strength prediction of notched samples, was used. This criterion is related to the point stress concentration criterion (see [Whitney, 1974]). This new criterion [Puhui, 2002] was verified by experimental results for a variety of composite materials and lay-ups, using tests by the authors and results from the literature. It should be noted that this analysis considered delaminations for the composites with nearly quasi-isotropic lay-ups. The delamination shape in the highly anisotropic materials or fabrics subject to impact (for which a rhombic or star-like shape of the delamination is not uncommon; see, e.g., [Tan, 2005]), was not within the scope of this analysis. Therefore, the LBPF criterion may not be reliable for analysing the CSAI influence of the projectile shape or delamination for strongly anisotropic composite materials.

As mentioned at the beginning of this subsection, CSAI prediction is not straightforward for sandwich materials. Semi-empirical equations are common for such materials. For example, a study conducted in paper [Dobyns, 1995] employed a range of analytical relations typically used for undamaged sandwich materials, such as

$$\sigma_R = A\,(E_x E_c G_c)^n \ ,$$

where σ_R is the residual strength, E_x is the facesheet elastic modulus, E_c is the core compression modulus, G_c is the core's shear modulus, and A, n are constants. A more flexible formula that is also described in the paper [Dobyns, 1995] follows a military standard and the formula's parameters contain the face-sheet thickness t_f and the core thickness t_c:

$$\sigma_R = B\,[(E_c t_f)/(E_x t_c)]^{0.5} E_x/(1+0.64K), \tag{8}$$

where $K=\delta E_c/(F_c t_c)$, F_c is the core's compression strength, and δ is a face sheet waviness parameter that can be associated with a potential of the face-sheets to damage/buckle. An attempt to validate these formulas against experimental results for damage that is near BVID and for sandwich materials with a variety of cores (materials routinely used in the RAH-66 helicopter structure) has been undertaken in this study. The analysis showed that equation (8) can be fitted to the test results with the selection of an appropriate δ for the polymeric core sandwich materials (the cores are Nomex, Korex, and HFT – fibreglass/phenolic honeycomb). However, the formulas failed to fit the test data for the aluminium core sandwich material. It should be mentioned that in the paper [Caprino, 1984], model (7) (Caprino's model reviewed earlier in this subsection), which was used for

CSAI prediction for conventional composites, was fitted successfully to CAI test results for graphite/epoxy-faced honeycomb panels.

7.5 Repair to structure. Certification of damage and repair

Battle Damage Repair (BDR) is closely associated with the ballistic damage of a military aircraft. This is a complex study field because characteristics of a repaired structure need to be within the margins of numerous design allowables. The major cause of degradation of structure characteristics after a repair is the joints of a repair patch with the structure. A general review of this topic can be found in a recently published monograph [Tong, 2003] composing several papers from leading scientists in this area. This review is devoted to a mathematical evaluation of repair joints and repaired structures along with experimental verification of the evaluation methods. Certification provides a user with information on how critical the damage of a specified part of an aircraft can be to the safety of the entire structure, so structure vulnerability is closely related to the certification issue. The character of damage due to ballistic impact (e.g., the delamination zone) and the residual strength are important for certification and for making further repair that are, in turn, subject to certification (see [Baker, 1997]).

A helicopter structure might be represented as a variety of potential targets to battle damage threats. Individual requirements (primarily, residual strengths) are ensured by requiring that structure components pass a certification process. A wide range of requirements can be imposed; for example, the typical certification process for metallic aircraft structures involves static strength, fatigue, damage tolerance, and durability. In other words, after an analysis of which specified threats, structures, and materials are involved, the specific damage produced by a specific threat can be assessed, resulting in the determination of the tolerance of the material/structure to the specific threat. The first target in the way of an impact threat is likely to be the aircraft/helicopter skin that covers and protects the primary structures, electronic and hydraulic equipment, and the crew. At the same time, the skin may carry significant structural loads. As a result, composite materials are of particular interest in studies of damage tolerance in battle conditions, because composite materials are very likely to be skin materials.

The allowable range of changes in structural response characteristics (e.g., the residual strength of the skin) is obtained from certification. For example, from the viewpoint of air-structure survivability, impact damage could be categorised as permissible if completion of a mission is possible or enough time is available to make a necessary repair before a crash. Thus the categorisation of allowables can be structured as an analysis of a set of case studies. For example, paper [Rašuo, 1997] reports on a case study of the ballistic damage of a helicopter tail rotor blade made from a composite. A 7.9 mm calibre projectile fired by a shoulder weapon produced the ballistic damage. The tail rotor blade was a composite structure filled with a foam core, fibreglass filament spar, some carbon filament embedded along the trailing edge, leading edge polyurethane protection strips, and an 18-section laminated fabric skin. The root of the spar was subjected to penetrating damage. Fatigue and vibratory tests were conducted and the results showed no unsafe degradation of the

vital mechanical characteristics. The safety limit was considered to be minimum of 30 minutes flight to reach the emergency-landing site.

However, it is impossible to consider all possible case studies, so more tractable approaches are necessary to evaluate the structure survivability. Certification is aimed at helping in this evaluation since, during certification of a structure subject to damage, a range of load modes and damage locations within a structure are considered. Impact damage can be classified by its extent into Barely Visible Impact Damage (BVID) and Visible Impact Damage (VID). The danger of BVID is that invisible composite delaminations may result in reduction of the composite's strength. BVID is very hard to identify, so design parameters should cover the possibility of delaminations associated with BVID (for example, exceeding the allowables of an undamaged composite part by the margin of safety mentioned in subsection 2.1). Ballistic damage can also be classed as 'discrete source damage' when related to BVID, resulting in a residual strength below DLL (see subsection 2.1). For such damage, the damage tolerance from the certification viewpoint is considered in paper [Shyprykevich, 1997]. Analytical solvers have been surveyed in this paper for after-impact analysis of elliptically shaped delamination due to impact. Two load modes (normal and shear) are typical for the determination of a critical energy release rate. The double cantilever beam test and notch flexure test have been used in this paper as the appropriate experiments to deal with these load modes. However, it should be noted that the loads are unlikely to be present in a pure mode. For example, one difficulty with assessing the damage due to ballistic impact is that the loads being applied to the material under impact can be a very complex mix of load modes.

New structural designs may require enhanced properties for the composites involved, and modification of materials may be needed in order to reduce vulnerability. For example, the selection and fitting of a composite material to design requirements is described in paper [Kedward, 1997] for a composite fan blade of an aircraft engine subjected to high-velocity impact by a soft body (bird ingestion). Fan blades are especially vulnerable to impact or other damage threats because they operate at high dynamic loads. Therefore, the damage tolerances for these parts are tight, requiring special attention, including in design criteria and the analysis techniques for their evaluation (see [Sun, 1975]).

Any damage repair is also considered within certification guidelines. Battle damage repair, such as the repair of a delamination/crack, is an example of a repair. Several examples of patch repair have been considered in paper [Baker, 1997]. A structure that has been repaired should meet the certification requirements for damage tolerance (e.g., for residual strength), durability, etc. Historically, composites were used as repair material, but now they are routinely used as primary structural materials in helicopters. Therefore, the new challenges faced by engineers are repair and certification of the repair for composite and sandwich material parts of a helicopter. The procedure for the repair of a sandwich material with an aluminium honeycomb core (the material used in the RAH-66 helicopter structure) is outlined in paper [Llorente, 1995]. The repair in this study was followed up by testing using a gauge-instrumented sample. The influence of the repair patch lay-up on the compression test results was studied in this work. An evaluation method derived from

analysis of these results, was used for evaluation of the repair and assessment of the characteristics of the repaired structure.

The major concern when repairing a sandwich structure is the necessity of removing the damaged part of the core area and replacing this part with a new piece of core. The introduced gap between the remaining core and the replacement piece, which is filled with adhesive, can be a significant concentrator of stresses. This issue was addressed experimentally and theoretically (using FE modelling) in paper [Ruddy, 1995]. Load transfer mechanisms were analysed in this paper using the anisotropic elasticity material model, and the effect of excessive patching was considered as well.

The mechanical characteristics of a repaired patch or a joint that connects a composite part with a structure may be almost as good as those of the original undamaged structure. Surprisingly, the failure of a repaired structure frequently occurs at a location other than a joint. For example, [Cao, 2004] reports on flexure tests under three-point bending of a hybrid substructure, which combined a sandwich composite-skinned beam with a steel beam joined with a co-infused perforated joint.. This study demonstrated that the strength of the hybrid joined structure was approximately 90% of that of the original composite/foam sandwich beam. Failure of the hybrid structure during three-point bending tests occurred not at the joint, but in the composite skin under compression. This may have been due to variable stiffness of the hybrid-system components resulting in a high curvature and local compressive deformation of the composite beam part.

Patch repairs are usually either bolted or bonded. It is generally accepted that a better quality of a composite patch repair can be achieved with adhesive bonding. Residual stresses after the curing of the adhesive can be important, especially for composite/ metal repair (see a relevant study [Ramani, 1997]). Paper [House, 1997] raises the possibility of using viscous joints in order to absorb energy under loading. Thermal residual strains and the total residual strain were measured in paper [Albat, 1997] for an elevated cure temperature when boron/epoxy patches were bonded to a cracked aluminium structure. Embedded gauges were used for the strain analysis in this study. Experimental monitoring of surface strains and residual surface strains in the vicinity of bonded patch repairs is described in papers [Galea, 1997; Tapanes, 1997]. Surface mounted strain gauges were used in these studies in order to detect and monitor crack growth beneath the composite patches.

The modification of bonded repairs using patch interlayer inserts to increase the bearing stress, has been suggested in paper [Mirabella, 1997]. The idea of interleaving in composite materials (see, e.g., [Masters, 1989]) was exploited in this study in order to reduce interlaminar micro-stresses. The types of joints and repair configurations may be manipulated to improve specific modes of damage resistance. For example, the wavy-lap bonded joint has been analysed experimentally and numerically (see paper [Ávila, 2004]). For single-lap joints, failure typically occurs due to tearing whereas wavy-lap bonded joints tend to exhibit shear failure [Ávila, 2004]. A stepped-lap joint was considered in

paper [Kim, 2004c] and the influence of joint geometry on the tensile and shear strengths of the bonded structure and the fatigue life of the joint was studied.

Load amplitudes and durations, load modes, and the methods of application of loads to a structure are changing with the development of novel air platforms, advanced regimes of their exploitation, and novel weapons systems. Changes in the character of loads and structures require non-traditional methods for monitoring susceptible parts and repairs/modifications. For example, the use of constitutive models for the evaluation of performance of composite parts along with the development of new approaches to certification has been demonstrated in paper [Jones, 2004]. It should be noted that fracture criteria used in this paper are traditional and do not take into account possible damage accumulation.

The strain rate sensitivity of material is generally accounted for in studies of composite materials with polymeric matrices under dynamic loads. Although it is generally believed that the strength of bonded joint repairs are not dependent on the loading rate, a detailed experimental study of the load rate dependence and the load history effects on the failure load in the bonded composite patch repairs is reported in paper [Chiu, 1997b]. The influence of the type of repair (single-lap joint or double-lap joint) on the load rate-load failure dependence was also reported in this study. An experimental study [Wang, 1998] considered load rate effects on the strength of adhesively bonded double-lap joints and the overlap length was reported to be a significant factor. For a large enough overlap under normal conditions the rate sensitivity was negligible. However, for a hot-wet environment the rate sensitivity increased significantly. This rate sensitivity of the joint-structure strength was probably caused by the activation of a viscous damage mechanism in the joint adhesive (activating the polymeric nature of the adhesive in this environment). Thus, the adhesive's rate sensitivity affected the rate sensitivity of the joint.

Highly instrumented monitoring of joints is needed in order to obtain the information required by advanced modelling tools. Such monitoring is also becoming common in order to increase the lifetime of air-structures, because secondary structures may be routinely repaired on military aircraft. In order to follow certification guidelines, the methods of monitoring a repair during its life are being developed and introduced into service. The use of fibre gauges (fibre Bragg grating sensors) for monitoring possible disbond in a repair accompanied by release of thermal residual strain was reported in paper [Baker, 2004]. This paper also outlined the applicability and limitations of the health monitoring method for the aircraft components.

7.6 Predictive capabilities of the repair quality

Predictive capabilities for repair design and for analysis of structures after repairs are still rather limited, but this is a quickly developing area. Conventional finite-element techniques can be used for analysis. For example, a real aircraft structure may be complicated by hybrid structures, such as rivets in the wing. A stress analysis of laminates

stiffened with rivets is considered in paper [Lee, 1997] using the ABAQUS finite element software.

Paper [Dodd, 1989] describes an expert system for the battle damage repair of aircraft structures. The system capacity is limited to a damage size of 17.5 cm and to structures subject to tension. Two types of repair are processed by the system: i) bolted and ii) bonded patch repairs. For the bolted repair case, the system uses the BREPAIR program that employs boundary collocation to determine stress distributions in the skin and patch. For bonded repairs, the system uses two programs. One of them is the finite-element PGLUE program for analysis of bonded repairs. The second is the BJSFM program that evaluates the stress field around a loaded or unloaded hole. The system may suggest metallic or composite materials and adhesives as options for the skin and repair patch. Circular or elliptical damage zones of given sizes are analysed. The skin is input as a rectangular area with given dimensions and bi-axial or shear loading in the in-plane directions. Patch layup is also an input parameter. The system uses a number of rules to evaluate the quality of the selected repair (overdesigned or underdesigned). The evaluation is conducted by the system in a number of iterations using the repair quality as a stepping criterion. In the cases of overdesign or underdesign, an additional iteration is introduced to achieve the optimum repair design.

For composite patch repair, stresses in skin, patch and adhesive are individually analysed in paper [Rastogi, 1997]. The effectiveness of several software packages is assessed. The PGLUE package assesses stresses and deflections in the skin, patch and adhesive with a quasi-three-dimensional finite element analysis. The MOSAIC program uses a three-dimensional variational analysis and calculates stresses in composite-bonded joints at the skin-adhesive and patch-adhesive interfaces. Whole-scale stress analysis is conducted with the commercial finite-element package ABAQUS. ABAQUS and MOSAIC analyses are generally similar, but the PGLUE analysis based on a plane stress assumption differs significantly from the ABAQUS/ MOSAIC analyses in the assessment of interface stress. Researchers are also looking for simpler and quicker approaches. For examples, design of bonded composite patches using an analytical technique for the approximation of a crack as an elliptical opening is considered in paper [Wang, 1997].

General repair assessment software packages evaluate repair quality from the certification viewpoint. These packages deal with input parameters in terms of the design allowables plus integral parameters of the patch and they produces allowables for the repaired structure. However, the margins used for evaluation of repaired structure may underestimate the strengths for specific material and dimensional repair combinations of patch and main structure. Therefore, significant weight penalties are possible due to the underestimates. For this reason, more detailed evaluations/ modelling of the repair characteristics may be required.

Typically, analytic approaches to the modelling of joints and repairs are obtained from classical solutions based on theories of elasticity and elastic-plasticity. An analytical approach is developed in paper [Zou, 2004] for stress analysis of adhesively bonded

single-lap and single-strap joints. Both metallic and composite joints were assessed with this approach within elasticity assumptions and the plate theory approximation. The estimates were compared with available finite-element solutions and the paper concludes that the approach is a simple and convenient tool for designing joints in order to minimize stresses in the joined structure.

A different way of derivation of the analytical formulas for assessment of repair quality can be explored when finite-element analysis is used for preliminary assessments. For example, a finite-element calculation of maximum stress in the vicinity of single-lap joints is described in paper [Reis, 2005]. The results of the calculation were used to derive an equivalent stress for a failure criterion. The concentration of stresses due to bolts in bolted joints and the repair strengthening due to stress variation caused by the composite patch thickness are analysed numerically in paper [Kradinov, 2005]. A complex potential theory within the elasticity framework is used for this analysis. A parametric FEM study was conducted (see paper [Kelly, 2005]) for a single-lap bolted joint with CFRP adherents. The parameters of the study were the adherent thickness, adhesive thickness, modulus of the adhesive material, overlap length, and pitch distance. The numerical results on load transfer were verified by experiments where the bolt was instrumented with strain gauges.

The repair problem is considered in paper [Belhouari, 2004] using an FEM approach for the analysis of the repair of a crack in a metallic structure by a boron/epoxy patch with different modes of loading. Detailed numerical modelling confirmed the benefits of a double sided patch over a single sided patch repair. The effect of stabilization of the stress intensity factor was compared for both types of repair, which allowed an optimisation of the patch dimensions and a reduction of the repair cost. It should be noted that elasticity theory was used for the analysis, which may reduce the validity of the results in some applications.

Paper [Aymerich, 2005] describes in detail the finite element modelling of an unstitched and stitched overlap joint. The FEM detailed model used by the ANSYS package allowed an introduction of delamination at the adhesion layer. The energy release rates of tensile and shear modes and the stitch tension stress were calculated for tension and fatigue test conditions. The calculations show that, for the unstitched joint, the rates G_I and G_{II} increase with interface delamination between the adherents, whereas for the stitched joint, G_I is nearly zero after the delamination passes the stitch line. These calculations explain the experimentally observed slowing down of fatigue crack propagation.

Traditional FEM approaches dealing with stress analysis based on elasticity theory and classic elastic-plasticity may be not relevant to repairs/modification to aircraft structures under all conditions of loading and loading rates. For example, the traditional approach under cyclic loading with large deformation may produce significant inaccuracies for the areas of an aircraft where repair/modification is present (see [Jones, 2004]). Therefore, an advanced model, such as a rate sensitive constitutive model may need to be employed in order to validate certification of a repair.

8. Conclusions

The conclusion provides a summary of the main points made in this literature review and emphasises the importance of the examined area (experimental and modelling approaches in studies of composite materials' response to impact) for the assessment of air structure vulnerability. The review is linked to the Battle Damage Repair program and vulnerability of a helicopter platform to identify likely fruitful research areas for future investigation.

This review has identified the following main issues/focuses in studies of composite and cellular material response to impact: (1) certification and types of threats; (2) characterisation of advanced materials; (3) shock response of materials; (4) damage resistance at LVI; (5) damage resistance to ballistic impact; and (6) damage tolerance and repair.

The following summarises the present literature review and identifies major gaps.

Structure certification and types of threats

Conducting full-scale tests on air structures made of composite materials is expensive. Full-scale tests do not provide valid data for the complete range of possible threats because it is impossible to include all possible environments and threats. Therefore, the current trend in air structure testing is characterised by the extensive use of modelling tools, such as detailed finite-element modelling of the sub-component structure. Constitutive modelling is presently being used in detailed analyses of sub-component response, such as analysis of the response of structural joints in transient conditions.

The use of modelling tools has a number of advantages in comparison to full-scale tests. Modelling tools can be validated by small-scale coupon and sub-component laboratory tests, which allows a significant cost reduction. Modelling provides more detailed data because the small-scale test assemblies can be equipped with gauge-monitoring instrumentation and the test set-ups can closely approximate real structures. Also, modelling allows the analysis of air structure responses to different types of threats, which means that vulnerability to emerging threats can be quickly assessed.

In order to develop adequate modelling tools and to validate models and tools, validation tests should be properly set up and interpreted. In other words, in order to make use of modelling tools, a substantial methodological foundation needs to be established. This involves, as a necessary stage, a critical analysis of existing approaches and experience based on their applicability to assessment of structure response to impact and blast threats. In order to assess the state of art in studies of composite material response to different types of threats (impacts), it is necessary to discuss the adequacy of existing tests, test tools, and conditions employed as well as the goals of experiments and the assumptions used by researchers when they interpret tests results/data. Major gaps in the current

studies may then be identified. Such an analysis is a preliminary yet a necessary stage in order to develop a robust expertise/testing framework for helicopter vulnerability assessment.

Tailored threats to specified targets made of composites or cellular materials are currently in operation. Although these are the primary threats to air structures in well-developed conflicts, they are not the only threats that are possible. For example, threats in peacekeeping operations range from low to hypervelocity impact by compact impactors, and from blast load due to helicopter gun operation to synergistic blast-fragmentation effects. All of these types of threats are assessed in the literature, but as this literature review has shown, there is a technology gap in the analysis of the synergism due to the blast-fragmentation effects of novel warheads (including man portable weapons) and HEI projectiles. The issues of guidance accuracy and fusing aggravate the analysis because these factors increase the stochastic component of the weapon effect.

Characterisation of advanced materials

Characterisation of advanced materials involves the assessment of elastic, irreversible, and fracture properties. The assessment of different types of properties in different materials (composites and foams) requires the use of a wide variety of testing machines and methods. Due to the variety and complexity of these methods, it is particularly useful to analyse their possibilities, restrictions, and gaps in order to select those studies that provide most reliable data and/or to develop our own assessments. Such an analysis has been conducted in this review, and the list below summaries the outcome.

a) Assessment of the elastic properties of composite materials
Determination of the elastic properties of composite materials can be reliably obtained with quasi-static testing machines. These machines record stress-strain response in conditions when the stress state equilibrates and is uniform within a sample. Critical analysis of the tests and their interpretations has shown, however, that there is a technology gap in studies of elastic properties at high strain rates. For deformations below the elastic limit, samples in SHPBs are not at stress equilibrium, which makes it impossible to obtain material stress response during the initial stage of the sample loading. Therefore, the only data that may presently be used for an assessment of the rate sensitivity of elastic properties in composites are the data obtained with servohydraulic testing machines at rates of the order of tens of inverse seconds.

b) Assessment of the elastic properties of foams
For foams under tension, the elastic modulus can be obtained in the same way as for conventional materials. This is not the case for foams under compression where elastic behaviour may be highly non-linear, making it necessary to take material kinetics into account.

c) Yield stress and strength of composite materials
The yield stress and strength of many composite materials at high strain rates can be obtained routinely using SHBs whose input and output bars have a relatively large diameter, so that samples containing a representative volume of material may be tested. However, strength effects and the extent of loading of a sample make the SHB tests sensitive to experimental factors such as sample dimensions and the configuration of the SHB facility. Variations in these factors lead to variation in the achievable range of deformations. Ignoring these factors results in failure to correctly measure strength, which explains why contradictory data for the same material are reported in different publications.

d) Rate sensitivity of mechanical properties of composite and cellular materials
Rate sensitivity of mechanical properties has been reported for many composite and cellular materials. The rate sensitivity depends strongly on manufacturing and environmental (particularly, temperature) conditions. Manufacturing conditions may also contribute significantly to data scatter.

e) Characterisation at complex stress state
Presently, tensile tests with SHTBs are common, as are shear and torsion tests. However, the designs of SHBs for such tests require that samples be specially manufactured and mounted in the testing apparatus, which introduces uncertainties in results interpretation. Off-axis tests face the same problems as tests under complex stress states because the deformation of samples with unaligned fibres is performed under complex stress states. Widely published off-axis tests have mainly been conducted for composite samples with balanced structures. The uniformity of stress in samples subjected to off-axis testing (specifically, stress in samples with an unbalanced structure) and testing at elevated temperatures has not yet been completely verified.

f) Fracture properties of composites
Many composites exhibit similar features to brittle materials and the fracture properties of composites have been studied for a long time. Recent studies indicate a rate sensitivity in the fracture energy release rate and this is a factor to be taken into account. In order to reveal the actual rate sensitivity of a composite response under SHPB and SHTB tests, scaling factors for brittle composites (such as carbon/epoxy composites) and for composites with weak interlaminar bonding should be investigated further. Analysis of the literature has shown, however, that the dimensional factors of a composite sample, which affect the sample's fracture onset, have not yet been systematically analysed.

g) Characterisation of cellular and porous materials
There is a significant technology gap in the SHB testing of cellular and porous materials. Cellular materials cannot be tested reliably with traditional SHPBs because only a small deformation can be achieved in a conventionally sized small sample. A small sample, however, may not contain enough cells for the sample to be representative. There is a large misimpedance between cellular material and the steel of which conventional SHPB bars are made. This misimpendance results in significant attenuation of the signals delivered to

SHPB gauges. Therefore, the important issues that need to be resolved when testing cellular materials with SHPBs are the signal quality and the representative size that allows the sample to achieve equilibrium. Novel SHPB designs and methodologies of interpretation of the recorded signals are still being developed.

h) The history dependence of material properties

This review has also identified technology gaps in such areas as testing of pre-loaded or pre-damaged (repeatedly loaded) samples for static and high-strain rate conditions and SHPB testing under complex stress states, and testing to determine sensitivity of material properties to the load history. It is argued that it is necessary to take into account the material property history when analysing tests for pre-loaded and pre-damaged samples. It is important because damage tolerance is usually evaluated for components that have been previously repeatedly damaged or loaded, and mechanical properties of materials for pre-damaged components are not identical to those of the original.

i) In-situ monitoring

Non-destructive evaluation (NDE) extends traditional methods, such as C-scanning and SEM inspection, to in-situ monitoring using spectrometry, interferometry, and smart materials monitoring principles. For instance, X-ray tomography allows in-situ evaluation of the evolution of material structure including delamination and debonding zones through the sample thickness. NDE studies are being extensively developed and the major gap is application of NDE to actual problems. In practice, the NDE methods have not been widely applied to directly monitor changes in material structure during a transient loading event.

Shock response characterisation

The shock response of composites is of utmost relevance to impact resistance characterisation. This review has shown that there are many novel experimental techniques in this area. These techniques involve direct stress gauge measurements of composite materials for plate impact conditions. Gauge embedding sandwich set-ups are employed for stress gauge measurements of cellular and porous materials and high-speed photography and interferometry are used for monitoring the behaviour of composite targets under high-velocity impact by compact projectiles. Interpretation of plane wave data is, however, a technology gap. Traditional methods of interpretation do not work for characterising composite impact resistance because those methods are based on the principles of classical shock wave physics. Within this classical approach, the sample state is calculated from the jump conditions (the Hugoniot relationships). This approach does not, therefore, allow a consideration of the state non-equilibrium in the complex shock wave that propagates in advanced (composite and cellular) materials. Measurement of temperature or internal energy in a target material in dynamic conditions is also a technology gap, which is of particular relevance to the assessment of the impact response of cellular and porous materials, but physics limitations may restrict development of appropriate methods of measurement. Experimental studies of the response of composite and cellular materials to explosive loads and blast-fragmentation threats are still required.

Theories involved in the analysis of the behaviour of composite and cellular materials under high-velocity impact are being extensively developed. The following are families of models that deal with several structural levels of materials: i) models based on an averaged description (anisotropic elasticity and elastic-plasticity); ii) computational models based on a description of a composite/cellular material as a combination of constituents/cells (models with separate treatment of constituents or with building block arrangements); iii) material models obtained using structure homogenisation (phenomenological models); and iv) models involving a meso-level description. However, there is lack of relevant data that would allow one to describe the necessary kinetic behaviour and dynamic interaction of material constituents. There is also a lack of constitutive theories describing the kinetic behaviour of honeycomb and cellular materials for complex stress states. A history-dependent description of the deformation of cellular materials is a technology gap.

Numerical techniques for the evaluation of composite impact response involve both structural and hydrocode modelling. Structural finite-element codes traditionally employ widely implemented models of isotropic and anisotropic elasticity. Hydrocodes deal with both well-known models available from hydrocode databases and novel material models. The finite-element grids of composite structural materials are obtained with advanced meshing pre-processors that allow a modeller to design fairly complex composite and honeycomb structures using the constituents/cells combination approach and a range of pre-processors for this purpose is available. Although the erosion option in hydrocodes is still the most popular, it is being gradually replaced with techniques for the calculation of delamination and constituent damage. The continuum damage mechanics (CDM) approach is extensively used, mainly for modelling matrix damage and associated elastic modulus degradation. However, the lack of closure data for relevant CDM constitutive equations is the major drawback to progress in this direction. In general, modelling of the physical fracture behaviour of composite and honeycomb materials is a technology gap.

Modelling realistic stress-strain responses of composite materials with constitutive rate sensitive models is commonplace, although it requires experimental data at high strain rates. However, realistic prediction of impact response using models with constitutive parameters fitted to the high strain rate data obtained from independent experiments, is an issue. The description of anisotropic materials for complex stress states and with deformation-induced rotation of the material symmetry axis (spin) associated with finite deformations during high-velocity impact is still an issue when implementing models in numerical codes and associating the model parameters with experimental data. Excessive simplification of modern models for cellular and sandwich materials is an issue. More realistic models are needed that address the physics of transient, complex stress states and the history-load behaviour of foams.

Ballistic impact by compact projectiles against composite targets has been widely studied. Embedded gauges and high-speed photography are used for the analysis of failure modes and energy transfer mechanisms in targets. The redistribution of projectile energy over a

wider area, thus reducing the load concentration, is considered in a variety of ways in studies when hybrid targets, buffer and sacrificial targets, and appliqué armour are used. A modern trend to increase the protective capacity of composite targets is the tailored introduction of structure variations during manufacturing in order to increase the absorbed energy of the material and to reduce the residual kinetic energy of a projectile after perforation of the material. The effect of projectile friction with a composite target on the absorbed and residual energies is yet to be clarified. Damage to sandwich materials with honeycomb cores under non-ideal regimes of impact (obliquity, yaw, and tumbling factors before the encounter, movement of target, etc) is highly sensitive to the parameters of impact. However, studies of target damage in such conditions are required and this is a technology gap.

Experimental techniques for the study of the behaviour of a composite target subject to ballistic impact by a compact projectile involve a wide range of high-speed photo-instrumentation and embedded gauge techniques for monitoring stress and strain. However, in-situ damage observation is still a technology gap. Modelling of an impact event may be performed with various models developed in the area of material modelling. However, there is lack of theoretical and experimental studies of oblique and non-ideal impact, although such impact events are the everyday reality in the battlefield. In particular, there is a need for constitutive modelling of the synergism of foam material response to blast-fragmentation effects.

Damage resistance at low-velocity impact

Composite damage resistance to low-velocity impact (LVI) is a well-developed research area. For LVI testing, the load-displacement curves allow the peak force and absorbed energy of a sample material to be determined. However, the absorbed energy is defined differently by different authors. Also, the fracture onset (and fracture in general as an association with the bearing capacity of a material-containing structure) deduced from the load-displacement curve is not clearly defined. Therefore, clear understanding of the correlation of a recorded response with the underlying physical process is still an issue. Environmental conditions (e.g., temperature) moderately affect target impact resistance for LVI conditions. Manufacturing conditions (arrangement of multiple layers, interleaving, and stitching) significantly affect the LVI resistance. At high impact energy, the most important factor seems to be the ambient temperature and that also increases the rate sensitivity. Rate sensitivity is claimed to be relevant for composites with polymeric matrix. Matrix cracking and delamination are prevailing modes of damage under LVI conditions.

Uniformity of deformation for low-velocity impact of a cellular material is the major factor in classifying failure modes of the material. Mechanical properties of the face-sheets of sandwich materials are critical in determining the LVI resistance of these materials. In contrast to composite materials, the loading mode is of prime importance to the resistance of these materials. This issue, however, has not been properly addressed yet. Damage patterns are not easily identifiable for honeycomb and cellular materials. Attenuation of the load stress down to a level corresponding to compaction stress and a high energy-

absorption capacity are attractive features of cellular materials. The energy absorption increases if the compaction stress and solidification strain increase. Therefore, it is appropriate to search for a cellular material tailored to a specified load, if the material can provide the lowest stress transfer and energy due to the load is absorbed by the material during the compaction stage. Cellular materials are used in combination with composite face-sheets and as components of hybrid materials. As a result, prediction of the behaviour of sandwich materials is difficult, and requires non-linear and kinetic descriptions even under LVI conditions. This lack of a predictive capability is currently a technology gap.

The effects of energy and velocity factors for LVI conditions have not yet been clearly considered. The velocity factor dominates over impactor energy (via variation of the impactor mass) for certain composite and sandwich structural materials. Also, the influence of the indentor shape is not addressed in detail and shape effects are not fully characterised in LVI studies. Repeated impact is not properly addressed, keeping in mind studies that demonstrate that damage and absorbed energy are related to the number of impacts in quite complex ways. Decreasing the impact velocity means that boundary conditions become more important. Boundary condition effects for LVI have been studied extensively, showing the influence of the indentor shape and the impactor velocity/energy on the affected boundary range.

Damage resistance to ballistic impact

Failure in composites under ballistic impact is mainly observed with high-speed photography and the stress level is verified with embedded gauges. The following failure mechanisms are reported in the reviewed literature: shear cut-out (plugging); fibre debonding, breakage, and pull-out; delamination; and matrix fracture. Studies of manufacturing/composition factors affecting absorbed energy and damage in composite targets, such as the lay up of structural materials or appliqué armour, are widely available in the literature. Reducing interlaminar stresses and interleaving is recognised as a method for reducing damage in composite targets (increasing ballistic tolerance). The energy absorbing effect has been exploited with multiple laminates and confirmed by studies of multiply-layer assemblies. Some publications suggest that in the low-velocity range, the energy absorbing capacity is higher for multi-layer systems, and that ballistic resistance is likely to increase using multi-layer system when compared to a single layer target of the same equivalent thickness. Appliqué armour backed by composites is reported as an advancement in the synergism of hybrid target effects.

Boundary condition effects are fairly limited for ballistic impact. They are typically limited to the range of 5-10 diameters of the projectile at the ballistic impact. Ballistic tests of composite and cellular materials with pre-damage and pre-load are few and this area is a technology gap.

Studies of shape factors affecting absorbed energy and damage are available. These studies show that blunt and spherical projectiles result in higher target damage than AP and ogival ones. It is reported that non-ideal conditions of impact, such as non-zero obliquity,

and moving target effects may increase the target damage significantly. A projectile encounter with a target at moderate velocities of impact for a non-spherical projectile, such as an AP projectile, can be unpredictable with respect to the obliquity angle, yaw, and pitch, so the encounter may result in non-ideal impact. Therefore, extensive controlled testing at ballistic ranges is required. Advanced facilities, such as a gas gun monitored by high-speed photography, are necessary for the ballistic evaluation of targets that are sensitive to the conditions of encounter.

The ballistic limit velocity V50 is the most widely used characteristic of ballistic resistance of a composite target for a given combination of projectile and target. However, there is no widely accepted definition of V50. Also, there are no unified ballistic performance (ballistic resistance) criteria except for V50. There is a simple criterion of evaluation that is the depth of penetration (DOP) in a witness plate behind the target. There is also a number of the efficiency criteria based on the DOP characteristic. The absorbed energy can be associated with V50. Ballistic damage is greatest at a velocity level just below V50 and is likely to increase with the obliquity angle. The Lambert-Jones formula (usually with the exponent 2) is the most often accepted link of V50 with the impact and residual velocities of a projectile penetrating a target. The influence of a composite structure on the absorbed energy/V50 at ballistic impact is quite moderate for structure variations on the meso-level (lay-up, the stacking sequence). However, the structure influence may be more significant on the micro-level where it affects the local structure geometry (e.g., 3D-systems, cloths with a small harness number, and stitched samples). In contrast to the ballistic response of the composite materials, sandwich and cellular materials may exhibit an increase in damage with an increase in impact velocity.

The action of warheads and other threats, which involve synergism of blast and fragmentation effects, means that combination of different strain rates occur in the targets. The behaviour of composites in such synergistic conditions is not commonly considered in the literature. Analysis of the simultaneous (synergistic) action of different strain rates upon a composite is a technology gap both in modelling and in experimentation. Sandwich materials are prominent for protective purposes in such synergistic conditions because face-sheets and a honeycomb core might be effective against loads at both ranges of strain rates (face-sheets for loads at rates corresponding to impact by a compact projectile and a core for loads at rates corresponding to the blast effect). Foam materials are frequently tested under hypervelocity impact conditions relevant to the vulnerability of space structures. However, cellular materials are sensitive to the conditions of encounter (obliquity, projectile shape, etc) in the ballistic range of impact velocities relevant to the vulnerability of a helicopter structure. A study of the encounter sensitivity of cellular materials is currently a technology gap. Models describing response to the widerange-strain-rate loads caused by explosive and fragmentation threats must include kinetic and non-linear descriptions of the material behaviour, which is also a technology gap.

Damage tolerance and repair

The damage tolerance of a material as a measure of residual bearing capacity is inseparable from the damage resistance as a measure of the ability of the material to resist impact loads and to absorb kinetic energy. The effect of impact on damage tolerance is still conventionally evaluated from VID (the hole) for the residual tensile strength and from BVID (the delamination) for the residual compressive strength. There is no such a rule of thumb for the modes of shear and flexure. Modes of load other than compression are occasionally used for evaluation of composite residual properties after impact (evaluation of stiffness under tension and flexure, flexural strength, tensile strength, etc). However, those properties are sometimes not well-defined and are used mostly for comparisons within a study. The reviewed literature demonstrates, for example, that tensile strength after impact is mainly sensitive to the visible hole diameter and is not sensitive to delamination, whereas compressive strength shows sensitivity to delamination as well. It appears that the compression mode of load is the most sensitive to internal damage and delamination, which is of particular importance for LVI, non-ideal impact and sandwich targets. Therefore, compression of damaged samples is the most sensitive test in respect to assessing the internal damage due to impact.

CSAI is a very popular damage tolerance characteristic. It is well defined for conventional and simple structural materials. However, with increasing structural complexity, the CSAI definition, where compression strength is typically associated with a sudden drop in the load force, can be difficult. Gauge and video monitoring of a compression event is used for clarification of the limit strength. However, the association of CSAI with a characteristic of the bearing capacity, which is of practical significance, is not clear yet. This approach could provide a structure with narrow margin allowables and improve the weight saving characteristics. Specifically, interpretation of CSAI data for sandwich materials is a technology gap.

A number of factors affecting CSAI are reported in the reviewed literature. Manufacturing and structural features (stitching, interleaving, etc.) affect CSAI for low and high-velocity impact. Environmental factors are more important for CSAI than for impact resistance, particularly under LVI conditions. Some sensitivity of CSAI to pre-load is observed. However, the pre-load factor seems to be critical for conditions of non-ideal impact and for impact against sandwich materials. This area is a technology gap. There is a trend to directly link CSAI with the delamination area. Delamination and internal damage have a tendency to reduce with increasing velocity of impact in the ballistic range and both are very sensitive to the projectile shape. In turn, the damage and uncertainties in the damage evaluation increase for non-ideal conditions of impact and for impact against sandwich materials with a cellular core. This area of study is also a technology gap.

CSAI evaluation is a well-established area for composite materials. The open-hole approximation, usually with an elliptic shaped hole or a low-stiffness inclusion, may be explored with the analytical tools that are currently being developed. The trend is to extend such analytical or semi-analytical tools into expert systems. The CSAI analysis of

cellular and sandwich materials is generally performed with simplified approaches based on evaluation tools for undamaged core material and face-sheets. The distribution of damage through the thickness for laminates and sandwich materials is an issue to be taken into account and methods of CSAI evaluation for sandwich materials is a technology gap.

Using a composite patch repair to increase the lifespan of an aircraft structure and to reduce operational costs is a common procedure. Traditional techniques for conventional metallic structure repair using composite patches are being replaced by techniques for composite primary structure repair. These new techniques involve various methods of joining and bonding. Certification is necessary in order to introduce a repaired structure into service. Methods of assessment of repair quality are still relatively simplistic (analytical and semi-analytical based on the delamination size). The modern trend is to extend the simple methods to expert systems covering a wide variety of situations and structural analyses. After-impact expert systems are fairly well-established for composite systems but there is a technology gap for evaluation of the repair of structures containing parts made of sandwich structural materials. For numerical assessment of repair quality and certification of the repaired structure, constitutive modelling may be used with the goal of restoring the mechanical properties of the repaired structure to as close to the original as possible.

Traditionally, metallic structure repair involved a composite patch. New techniques include composite and sandwich materials for both the base structure and the patch. The variability of combinations for structures and repair patches is expanding faster than development of repair techniques, including methods of joining that involve combinations of bolting and adhesive bonding. The current trend is to increase the complexity of the joint design (including profiled joints, interleaving in patches, etc) and to reduce bounds in evaluation of the repair quality by using more detailed evaluation techniques, such as finite-element and constitutive modelling. The complexity of the joint design aims at the minimisation of stresses occurring at pre-selected load modes. Such designs and evaluation techniques are well-developed for composites and metallic-composite compositions. However, compositions involving sandwich materials are still not often considered in repair designs and evaluations, and this area is a technology gap.

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A.D. Resnyansky

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19. ABSTRACT

The present review aims at a provision of scientific support to the introduction of the Tiger ARH (Armed Reconnaissance Helicopter) into service. The review examines more than five hundred recent publications on the impact response of composite and cellular materials which are constituents of modern air platforms, specifically, helicopters. Using the ARH in an operational environment makes ballistic damage assessment an important issue. This review focuses on the factors of material response associated with structure vulnerability, such as damage resistance and damage tolerance.

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